(4)



RD&E CENTER

# Technical Report

No. 13385

STUDY OF

PASSIVE FUEL TANK INERTING SYSTEMS FOR

GROUND COMBAT VEHICLES

SEPTEMBER 1988



Steven McCormick, Peter Motzenbecker,
and Michael Clauson
U.S. Army Tank-Automotive Command
ATTN: AMSTA-RSS
By Warren, MI 48397-3000

APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION IS UNLIMITED



U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH, DEVELOPMENT & ENGINEERING CENTER
Warren, Michigan 48397-5000

NOTICES

This report is not to be construed as an official Department of the Army position.

Mention of any trade names or manufacturers in this report shall not be construed as an official endorsement or approval of such products or companies by the U.S. Government.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188 Exp. Date: Jun 30, 1986

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION: Unclassified | 1b. RESTRICTIVE MARKINGS: None |
| 2a. SECURITY CLASSIFICATION AUTHORITY | 3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release: Distribution is Unlimited |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S) | 5. MONITORING ORGANIZATION REPORT NUMBER(S): 13385 |
| 6a. NAME OF PERFORMING ORGANIZATION: U.S. Army Tank-Automotive Command; 6b. OFFICE SYMBOL (If applicable): AMSTA-RSS | 7a. NAME OF MONITORING ORGANIZATION: U.S. Army Tank-Automotive Command |
| 6c. ADDRESS (City, State, and ZIP Code): Warren, MI 48397-5000 | 7b. ADDRESS (City, State, and ZIP Code): Warren, MI 48397-5000 |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
| 8c. ADDRESS (City, State, and ZIP Code) | 10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO. |

11. TITLE (Include Security Classification)

Study of Passive Fuel Tank Inerting Systems for Ground Combat Vehicles (U)

12. PERSONAL AUTHOR(S)

McCormick, Steven J., Motzenbecker, Peter F. and Clauson, Michael J.

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Final | FROM March 88 TO Sept 88 | 1988, September, 1st | 64 |

16. SUPPLEMENTARY NOTATION

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) | | |
|---|---|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Combat Vehicles | Fire Extinguishing | Fuel Tank Fillers |
| | | | Fuel Tanks | Fire Survivability | Reticulated Foam |
| | | | Passive Inerting | Fuel Systems | Fuel Tank Jacketing |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Many flammable materials are carried aboard combat vehicles, including fuel, hydraulic fluid, and munitions. A fire involving any of these can lead to destruction of the vehicle and injury to the crew. Ground combat vehicles have relied on fire extinguishing systems to protect the vehicles and crew, while aircraft use passive inerting techniques as well as fire extinguishing systems. The apparent disparity between ground combat vehicles and aircraft has caused the US Congress to direct the Secretary of the Army to examine the use of passive, multiple-hit, fuel tank inerting systems in tracked and wheeled vehicles.

This report examines passive fuel tank inerting techniques and provides an assessment of their applicability to ground combat vehicles. The extent of the hazard posed by the combat vehicle fuel tanks has been defined. The adequacy of the technology in reducing this hazard is evaluated for each technique considered. The current technology for the suppression of fires in and from vehicle fuel tanks available to and in use by the armed services, other government agencies, the private sector, and foreign (continued on reverse side)

| | |
|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL: Dr. James L. Thompson | 22b. TELEPHONE (Include Area Code): (313) 547-5780; 22c. OFFICE SYMBOL: AMSTA-RSS |

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

19. ABSTRACT (Continued)

armed services has also been examined. Attention was restricted to passive systems (systems which do not require any mechanical or electrical activation) which can suppress multiple occurrences of fire. Both fuel tank fillers and systems which surround the fuel tanks were considered.

A review of currently available passive fuel tank inerting technologies has shown that the majority of these techniques are not effective for ground combat vehicles considering the large antiarmor threats. A significant quantity of testing has been conducted which bears this out. An exception to this are fuel tank jackets which show great promise in improving ground combat fire survivability. Further development work must be done before this approach can be integrated into production vehicles or retrofitted into fielded vehicles. Proper fuel system and vehicle design, in conjunction with fire extinguishing systems, are still the most effective means available to limit the damage caused by combat and peacetime fuel fires. (SDW)

## TABLE OF CONTENTS

## 1.0. INTRODUCTION

This report, prepared by the Research, Development, and Engineering Center of the U.S. Army Tank-Automotive Command (TACOM), examines passive fuel tank inerting techniques and provides an assessment of their applicability to ground combat vehicles. The extent of the hazard posed by the combat vehicle fuel tanks is defined. The adequacy of the technology in reducing this hazard is evaluated for each technique considered. The current technology for the suppression of fires in and from vehicle fuel tanks was reviewed. The technology available to and in use by the U.S. armed services, other U.S. government agencies, the U.S. private sector, and foreign armed services has been examined. Attention was restricted to passive systems (systems which do not require any mechanical or electrical activation) which can suppress multiple occurrences of fire. Both systems that function within the fuel tanks and systems which surround the fuel tanks were considered.

Many flammable materials are carried aboard combat vehicles, including fuel, hydraulic fluid, and ammunition. A fire involving any of these can lead to destruction of the vehicle and injury to the crew. Ground combat vehicles rely on fire extinguishing systems to protect the vehicles and crew, while aircraft use passive inerting techniques, as well as fire extinguishing systems.

Various passive fuel tank inerting systems have been in use, under development, or investigated for aircraft applications for many years. Several techniques have proven effective in reducing or eliminating the potentially catastrophic effects of small-caliber ballistic penetrations of aircraft fuel systems. Use of inerting systems on ground combat vehicles has been limited to several test programs. No passive inerting systems have been fielded on Army ground combat vehicles.

This apparent disparity between ground combat vehicles and aircraft has caused the U.S. Congress to direct the Secretary of the Army to examine the use of passive, multiple-hit, fuel tank inerting systems for tracked and wheeled ground combat vehicles.[1]

## 2.0. OBJECTIVE

The purpose of this report is to provide recommendations on the use of passive, multiple-hit, fuel tank inerting

systems as safety and survivability enhancements for tracked and wheeled ground combat vehicles.

## 3.0. CONCLUSIONS

All available data pertinent to passive fuel tank inerting have been reviewed, and the following conclusions drawn:

- Passive fuel tank inerting techniques have proven effective to improve combat survivability in aircraft applications.

- The design of, mission of, and threat to aircraft and ground combat vehicles are very different. Inerting techniques that are successful in aircraft may not be directly applicable to ground vehicles.

- Active fire extinguishing systems will continue to be required to extinguish "peacetime" accidental fires (fuel leaks, etc.) even if an effective passive inerting technique could be implemented.

- Ground combat vehicle fuel fires normally occur external to the fuel tanks. Therefore, installing fuel tank fillers will not provide any significant benefit.

- Ullage inerting systems prevent a flammable fuel-air mixture from forming in the fuel tanks. Since ground combat vehicles are not susceptible to ullage explosions, this technique will not provide any significant benefit.

- Limited testing has shown that fuel tank jackets filled with an extinguishant can be effective in reducing or eliminating fires resulting from fuel tank penetrations by threat munitions.

- Self-sealing fuel tanks are designed to protect against small-caliber penetrations. They are not effective against the much larger ground combat vehicle threat.

- The current state of fire retardant fuel technology is such that the fuel is not ready for use in the battlefield environment due to logistical constraints.

- Design of combat vehicle fuel systems to improve survivability from munition impact can provide significant improvements. This method is most beneficial during vehicle design, but can be applied to fielded vehicles.

## 4.0. RECOMMENDATIONS

The following recommendations are made with respect to implementing passive fuel tank inerting techniques to improve ground combat vehicle fuel fire survivability:

- Passive inerting techniques should continue to be applied to Army aircraft.

- Advances in passive inerting techniques should continue to be monitored for application to ground combat vehicles.

- Fuel system design improvements (e.g., external fuel tanks) should continue to be implemented.

- The Army should continue to pursue improvements to its active fire extinguishing systems.

- Lessons learned from past and present test programs should be applied to future combat vehicle designs.

## 5.0. DISCUSSION

### 5.1. Background

Many flammable materials are carried aboard ground combat vehicles, including fuel, hydraulic fluid and ammunition. A fire involving any of these may lead to destruction of the vehicle and injury to crew members. Several approaches are used to reduce the vulnerability of these vehicles to ballistic attack. By reducing the vehicle's detectability and silhouette, and increasing its mobility, the probability of a hit can be reduced. Given a hit, improved armors can reduce the likelihood of penetration. Sound vehicle design and compartmentalization can reduce the risk of striking combustibles. But no matter the amount of protection afforded, a significant number of combat penetrations of the vehicle will cause vehicle fires due to antiarmor weapon advances and the sheer volume of combustible materials that must be carried onboard.

Ammunition propellant fires pose one of the greatest threats to ground combat vehicle survivability. Compartmentalization (with blowout panels, vents, etc.) and extinguishing systems can reduce the hazard to crew members and mitigate vehicle damage. Various techniques are under investigation to provide propellant extinguishing systems.[2] To reduce the risk of igniting hydraulic fluid, a nonflammable hydraulic fluid (NFHF) has been developed which uses chlorotrifloroethylene (CTFE) oligomers as its base fluid. The NFHF is not compatible with elastomers and sealants used in currently fielded equipment and redesign of selected hydraulic and gun recoil systems would be necessary to accommodate NFHF. The Air Force has adopted a NFHF for their Advanced Tactical Fighter and the Army is considering its use in the Armored Family of Vehicles.[3] Further discussion of ammunition and hydraulic fluid fire suppression techniques is outside the scope of this report.

To increase the survivability of a ground combat vehicle after a round has penetrated a fuel tank, two separate approaches can be taken, (1) create an environment that inhibits a fuel fire from beginning or propagating (generally referred to as inerting), or (2) include a system to extinguish the resultant fire before it significantly damages the vehicle or injures personnel. The preferred approach would be to prevent a fire from beginning; however, techniques for doing this against large-caliber threats have not yet been developed. Even if an effective passive inerting system could be developed for ground combat vehicles, a fire extinguishing system would still be required to extinguish accidental fires or fires that are not threat munition induced. A discussion of available fire extinguishing systems follows along with an introduction to fuel tank inerting.

5.1.1. Fire Extinguishing Systems. The inclusion of a fire extinguishing system in ground combat vehicles has been common for decades. Both the hardware and the extinguishing agent have gone through steady improvements over the course of time. The earliest systems (World War II era) consisted of only a portable fire extinguisher which was directed at the fire and operated by a crew member. Use of a portable fire extinguisher is usually ineffective on a large fire (e.g., a fuel fire in a vehicle) and jeopardizes the safety of personnel. The preferred method is to have a fixed fire extinguishing system with remote activation to flood the affected compartment with extinguishing agent. Fixed total flooding systems are designed to extinguish all fires in the

compartment and maintain an inert atmosphere for a period of time after activation. The extinguishers are mounted in a convenient location with internal and external (to the vehicle) activation handles accessible to the crew. This type of system has been in use for ground combat vehicle engine compartments since the 1950s.

Fixed total flooding systems were limited to use in ground combat vehicle engine compartments until the 1970s primarily because of the incompatibility of the extinguishing agents with personnel. To extinguish a fire in the crew compartment a small portable extinguisher had been the only fire fighting equipment available onboard the vehicle. While there may be fewer highly combustible targets in the crew compartment, a direct hit on a hydraulic reservoir or accumulator will lead to a catastrophic fire. Therefore, ground combat vehicles should include a fixed fire extinguishing system in the crew compartment.

An important part of any fire extinguishing system is the extinguishing agent that is used. As far back as the 1930s two fire extinguishing agents were commonly used, carbon tetrachloride ($CCl_4$) and carbon dioxide ($CO_2$). $CCl_4$ is a very effective extinguishing agent, but it is also highly toxic in closed spaces (e.g., the "buttoned-up" interior of a ground combat vehicle). $CCl_4$ is better suited than $CO_2$ for use in portable extinguishers which can be directed at the fire. Because of its toxicity, $CCl_4$ was not used extensively in U.S. ground combat vehicles. In contrast, $CO_2$ was and continues to be used extensively. $CO_2$ is suitable for use in total flooding systems as well as portable extinguishers. However, $CO_2$ requires such a high concentration to extinguish a hydrocarbon fire that it presents oxygen depletion problems when flooding crew occupied areas. Therefore, $CO_2$ total flooding systems have been restricted to engine compartment use. For extinguishing fires in the crew compartment, portable $CO_2$ extinguishers have been approved. $CO_2$ was the extinguishing agent of choice from the 1940s until the late 1960s.

In the mid 1960s (and again in the 1980s) Halon 1301 (bromotrifluoromethane) was evaluated against several other fire extinguishing agents including $CO_2$, Halons 1011, 1211, and 2402, and aqueous film-forming foam. These other agents all have significant drawbacks, primarily toxicity, which restrict their use in ground combat vehicles. Halon 1301 was determined to be three to four times more effective than $CO_2$ and less toxic than the other Halon

agents. Halon 1301 was established as the best compromise between agent effectiveness and toxicity. In 1969, Halon 1301 was approved by the Army Surgeon General as the only agent acceptable for use in fixed fire extinguishing systems in crew occupied areas of ground vehicles.[4] Since that time Halon 1301 has become the agent of choice for U.S. Army vehicle engine compartment fire extinguishing systems as well.

A major drawback to the early extinguishing systems had been that detection of a fire was dependent on the crew or other personnel in the vicinity of the vehicle. If a fire is allowed to go undetected for any length of time (and given sufficient fuel and oxygen) the fire can quickly grow out of control. During the last 20 years, considerable research has been directed towards the development of fire detection sensors for use in ground combat vehicles. The primary obstacles to sensor development were the packaging of the sensor in a small unit which would survive harsh vehicle environments and the elimination of false alarms to common stimuli (e.g., matches, flashlights, sunlight).

Fire sensors work on several different principles, the two most common being optical and thermal. Optical sensors detect a fire by sensing the optical radiation (ultraviolet, visible, and/or infrared) peculiar to a hydrocarbon (fuel or hydraulic fluid) fire. Thermal sensors detect a fire by sensing thermal radiation via the transfer of heat to the sensor. Any heat source of appropriate temperature will activate the thermal sensor. Optical sensors have the advantage of rapid response time (5 milliseconds for optical versus 5 to 10 seconds for thermal sensors), while thermal sensor response is not affected by dirty environments.

In the case of an automatic system using optical sensors, the time from fire initiation to fire extinguishment can be as short as 100 milliseconds.[5 6] This is fast enough that a fuel tank fire (from a munition penetration) could erupt and be extinguished before any damage to personnel and equipment from the fire alone would result. An optical system can be used in either the engine or crew compartment of a ground combat vehicle. Optical systems are currently used in the engine and crew compartments of the M1 Abrams tank, and the crew compartments of the M2/M3 Bradley Fighting Vehicle and the M992 Field Artillery Ammunition Support Vehicle (FAASV).

In the case of an automatic system using thermal wire sensing, the time from fire initiation to fire

extinguishment can be as short as 5 seconds.[7] This is fast enough that minimum damage will occur to vehicle components. However, this is too long for use in crew areas, as second and third degree burns can occur in less than a second. Given that crew members receiving greater than first degree burns will have impaired function, thermal detection systems are used only in non-crew-occupied areas.[8] A thermal detection system is currently used in the engine compartment of the M992 FAASV.

5.1.2. Investigating Agencies. The most active agency in the investigation of fuel tank inerting has been the U.S. Air Force, working primarily out of Wright Patterson AFB, OH. The Air Force is the most active for several reasons. First, combat experience in Southeast Asia (SEA) indicated the need for improvements in fire survivability. Second, aircraft are extremely vulnerable in the air; any damage can lead to a loss of flight capabilities. Third, in order to maintain the lowest possible weight, aircraft do not use any significant armor protection, and the fuel tanks are subject to penetrations by small-caliber weapons. Fourth, Air Force aircraft use JP-4 fuel, which is more volatile than JP-8 or DF-2, and is subject to fuel explosions. The types of fuel tank inerting systems investigated by the Air Force include fuel tank fillers, fuel tank jackets, self-sealing fuel tanks, ullage inerting gases, and fire-resistant fuels.

The Army has evaluated various fuel tank inerting techniques, the majority of which have been intended for application to Army aircraft. A limited amount of investigation has been done for ground combat vehicles. Early efforts to apply fuel tank inerting to ground combat vehicles were directed towards the M113 APC during the 1960s and 1970s due to the large combat losses experienced in SEA. The primary causes of the losses were the light vehicle armor and crew area mounted fuel tank. More recent tests have been performed on the M2/M3, M113, and the M992. The techniques investigated include fuel tank jackets, fuel tank fillers, and redesigned fuel systems. The Army has also extensively tested fire-resistant fuels for aircraft and ground vehicles.

The Marine Corps use the same or similar ground combat vehicles as the Army and have evaluated the results of Army programs. They have also evaluated passive inerting techniques for their amphibious assault and landing vehicles, including fuel tank fillers and external fuel tanks.

The Navy uses inerting techniques similar to the Air Force to provide increased survivability for their aircraft. Naval aircraft use JP-5 fuel which is much less volatile than JP-4 and similar to DF-2 in terms of ignitability. The use of inerting techniques with the relatively low susceptibility of JP-5 to spark/friction ignition is necessitated by the catastrophic nature of a fire aboard an aircraft carrier. The Navy has also investigated applications to their water craft. However, the majority of this work is not applicable to ground combat vehicles.

The Coast Guard has investigated techniques for use on smaller water craft and aircraft. Engine room fire reduction has been the main thrust of their investigations. Currently, no inerting systems are used except on fuel tankers which employ ullage inerting systems using engine exhaust gas.

The Federal Aviation Administration (FAA) has directed their investigations towards improving crash survivability of aircraft occupants. The FAA has extensively tested fire resistant materials, nitrogen inerting systems, and fire-resistant fuels.

Several foreign countries, including Britain, Germany, and Canada, have investigated passive inerting techniques. All have investigated fuel tank fillers. The investigations were primarily comparisons between U.S. industry-developed fillers and in-country-developed alternatives. Of particular interest are the Israeli findings. Israel, which has the most recent significant combat experience, does not use any passive fuel tank inerting techniques for ground combat vehicles, beyond sound fuel system design practices.[9]

5.1.3. Damage Modes. In the context of this report the damage modes of concern are all threat-munition induced. The threat is represented by any projectile that can potentially penetrate the vehicle fuel tank. The probability of penetration is dependent on round type and diameter, velocity, armor type and thickness, and angle of attack.

A serious problem caused by any fuel tank penetration is hydraulic (or hydrodynamic) ram. Hydraulic ram is initiated by the impact of a projectile into the liquid of a fuel tank. The projectile penetrates the tank and transfers energy to the tank wall and subsequently to the fuel. This causes an impulse load on the entry wall which may crack and petal. In traveling through the fuel, the

projectile continues to transfer energy to the fuel. As the fuel is displaced, a pressure field is generated and a cavity forms in the fuel behind the projectile. The cavity left by the moving projectile contains fuel vapor and entrained air which can ignite if the fuel-air ratio is correct. Oscillations occur as the fuel seeks to return to its undisturbed state, generating additional pressure pulses which expel fuel from holes in the tank and contribute to further structural damage of the fuel tank.[10 11]

Damage can also be induced by the projectile impacting in the volume above the liquid fuel, i.e., the ullage. The ullage has the potential to explosively ignite from a penetrating munition, if the fuel-air ratio is correct. The possibility of ignition occurring is directly related to fuel type and temperature, available oxygen, and ignition source. The resulting rapid pressure rise after ignition can cause significant structural damage to the fuel tank and the vehicle. Normal operating conditions for ground combat vehicles, however, do not usually produce ullage fuel-air ratios that will support combustion when using diesel fuel. As a result, ground combat vehicles that use diesel fuel have a very low incidence of explosive combustion in the ullage.[12 13]

Explosions vary in rate of reaction from deflagrations to detonations. A deflagration (a reaction occurring in milliseconds) propagates at subsonic velocities (on the order of 10 to 100 feet per second). A detonation (a reaction occurring in microseconds) is a chemical reaction that propagates at supersonic velocities (greater than 1,100 feet per second). Rapid growth fuel fires initiated by combat action result in deflagrations. The majority of fuel fires occurring during combat are started when a round penetrates the fuel tank. The fuel is pulled through the resultant hole and is distributed on surrounding surfaces. The fuel is then ignited by the energy of the penetrating round or a hot surface (engine, gun breech, etc.). The burning fuel can ignite surrounding displaced and stored fuel, rapidly engulfing the vehicle in flames. Analysis of Vietnam War battlefield losses showed that 16% of the M113s and 13% of the M48s lost were destroyed by fires.[14 15] The destruction process was started by a munition threat (direct fire, indirect fire or land mine) and was completed by a sustained vehicle fire. These percentages are expected to be significantly higher in a European scenario.

Accidental fuel fires are generally quite different from combat fires. The displacement of fuel and the ignition

source of the fire are different. The typical scenario involves a loose or abraded fuel or hydraulic line forming a leak. The leak continues until the fuel or oil is ignited (e.g., by an electrical spark or a hot engine surface). The fire may then spread to the main fuel supply, or a pool of fuel, and eventually engulf the vehicle. This chain of events occurs outside of the fuel tank and over an extended period of time such that most inerting techniques would not be effective. In this situation, a total flooding fire extinguishing system is the most effective method of controlling the fire. An Army Safety Center analysis of tracked vehicle fires from 1979 to 1984 shows that peacetime fires were located mainly in the engine compartment (69%).[16] Of those fires caused by vehicle system failures, 60% were petroleum, oil, and lubricant (POL) related and 37% were electrical. Fires were caused by improper maintenance (60%), operator/crew error (24%), material failure (13%), and material design (3%).

## 5.2. Current Fuel System Descriptions

In general, fuel systems of Army vehicles consist of fuel tanks, fuel filters, fuel/water separators, fuel lines and fuel pumps (tank, transfer and injection). The components of major vehicle fuel systems are described below.

5.2.1. Fuel System Components. A general description of each component follows.

- Fuel Tanks. The fuel tanks of most combat vehicles are located as close to the engine as possible. This reduces the required fuel pumping distance, fuel pump pressure, and shortens fuel line length. Fuel tank volume is maximized within the limitations of vehicle size; almost all space which is not used for the crew, equipment stowage, or a weapon system is utilized for fuel storage. The shape of the resulting fuel tanks can be very irregular. The general shape of the M60 Tank's fuel tanks can be seen in Figure 5-1. Multiple fuel tanks are usually "cascaded," i.e., several fuel tanks feed into one or two fuel tanks which supply fuel to the engine. Cascading is done by either transfer pumps or gravity flow. Materials and construction methods for fuel tanks vary widely between vehicles.

- Fuel Filters. Most fuel filters are heavy-duty commercial filters and are mounted directly on the

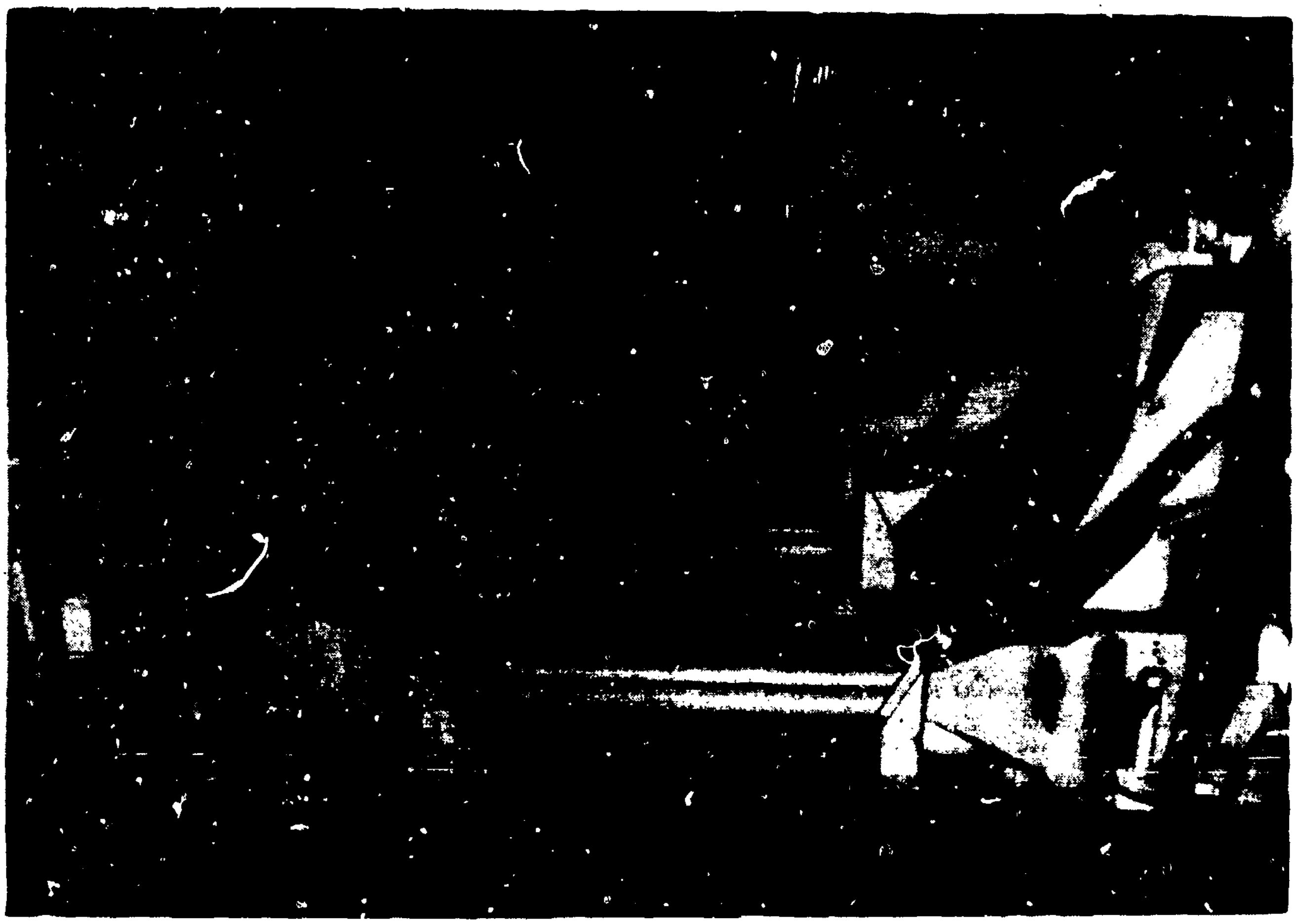


Figure 5-1. General Fuel System Layout
(M60A3 Tank is shown as example)

engine. Exceptions occur due to space constraints or access problems.

- Fuel/Water Separators. Most fuel/water separators are heavy-duty commercial separators and are mounted directly on the engine. Exceptions occur due to space constraints or access problems.

- Fuel Lines. Fuel lines are routed to use the least amount of line possible. Fuel lines are high-pressure braided steel and rubber hose or steel tube construction.

- Fuel Pumps. Fuel pumps are usually mounted internal to the fuel tanks, are of heavy-duty commercial construction and supply a fuel injection pump. Fuel injection pumps are engine mounted and are usually the engine manufacturer's standard pump. Fuel transfer pumps supply fuel from one fuel tank to another.

5.2.2. Major System Descriptions. The fuel systems of several U.S. military ground combat vehicles are described below. Table 5-1 gives a ready comparison of the major components.

The M1 Abrams Tank series uses six cast plastic (polyethylene) fuel tanks. There are two primary fuel tanks, one on each side of the engine in the rear of the vehicle. Two sponson tanks are located outboard of the primary tanks. Two secondary tanks are located in the front of the vehicle. Refueling can be done into the primary or secondary fuel tanks. Fuel in the secondary tanks is pumped to the primary fuel tanks and then to the engine injection pump. The two sponson tanks gravity feed into the primary fuel tanks which are gravity equalized. No isolation valves are used between any of the fuel tanks. The primary fuel tank pumps are actuated by a pressure switch. The main fuel line is pressurized during operation. Fuel for the engine flows through a pre-filter, a fuel/water separator and to a final filter. The fuel is then injected into the engine as needed (see Figure 1 in Addendum).

The M2 and M3 Bradley Fighting Vehicle Series (BFVS) has two cast plastic (usually Nylon-6) fuel tanks per vehicle. The basic vehicle configuration has the lower fuel tank pumping fuel to the upper fuel tank. The engine fuel filter is gravity fed from the upper fuel tank. The M2A1/M3A1 configuration is cascaded in reverse; the upper

Table 5-1. Vehicle Fuel System Characteristics

| Vehicle | Fuel Cell | | | Filter type | Reference |
|---|---|---|---|---|---|
| | Material | Total Vol | Count | | TM Series |
| M1 | Cast Plastic | 542 gal | six | plastic cartridge | 9-2350-255-XX |
| M2/M3 and M2A1/M3A1 | Cast Plastic | 175 gal | two | steel reusable | 9-2350-252-XX |
| M60 | Welded Aluminum | 385 gal | two | paper cartridge | 9-2350-253-XX |
| M113 and M113A1 | Welded Aluminum | 95 gal | one | steel reusable | 9-2350-257-XX |
| M113A2 | Cast Plastic | 95 gal | two | steel reusable | 9-2350-261-XX |
| M548 | mixed | 105 gal | three | steel reusable | 9-2350-247-XX |
| M577A1 | mixed | 120 gal | two | steel reusable | 9-2350-261-XX |
| M730 | mixed | 111 gal | two | steel reusable | 9-2350-585-XX |
| LAV-25 | Welded Aluminum | 71 gal | one | steel reusable | 08-0594A-XX |
| LAV-C$^2$, LAV-R LAV-M, LAV-AT and LAV-L | Cast Plastic | 71 gal | one | steel reusable | 08-0595A-XX thru 08-0650A-XX |

fuel tank gravity feeds into the lower fuel tank which is then pumped to the engine fuel filter. In either case, four fuel pumps are located in the lower fuel tank and the fuel fill port is in the upper tank. The fuel filter also acts as a fuel/water separator. Fuel flows from the filter to the engine fuel injection pump or to the cold start fuel pump. The engine fuel pump then supplies the injectors, with the excess fuel being returned to the lower fuel tank (see Figures 2 and 3 in Addendum).

The M60-series vehicles use two welded aluminum fuel tanks (sheet steel on very old models) that are bolted-in. The fuel tanks are located on both sides of, and slightly under, the engine. Refueling is done into the right fuel tank; the left tank has an emergency fill port. The two fuel tanks are gravity equalized. The interconnection hose contains a manual isolation valve which is normally open to permit filling of both tanks. Both fuel tanks house fuel tank pumps. Fuel is fed from the fuel tank pumps to the primary fuel filter and then to the engine fuel pump. The engine fuel pump feeds a secondary filter/water separator and the injection pump. The injection pump in turn feeds the individual cylinder injectors. After cooling the injectors, excess fuel is returned to the fuel tank (see Figure 4 in Addendum).

The M113-series vehicles have a mixture of welded-in /bolted-on, interior/exterior, aluminum/plastic fuel tanks, dependent upon the configuration, mission, and cost concerns of individual vehicle configurations. The M113-series vehicle chassis has become so well used that a general description is all that can be offered. Five basic fuel tank configurations exist, represented by the M113A1, M113A2, M548, M577A1, and M730. The fuel systems of the M113-series vehicles all have the same engine, fuel injection pump, fuel filters, fuel/water separator, injection pump and distribution head. One to three fuel tanks are used. When more than one fuel tank is used, the tanks are gravity equalized with no isolation valves. Fuel is delivered (pumped or gravity fed) to the injection pump and then into the distribution head. Individual injectors meter fuel into the engine cylinders as required. A pressure valve on the distribution head permits excess fuel to recycle back to the fuel tank(s). (See Figures 5 through 9 in Addendum).

The Light Armored Vehicle (LAV) is a wheeled fighting vehicle used by the Marine Corps. The LAV series uses two fuel system configurations. The LAV-25 uses a welded-in fuel tank mounted in the rear floor area. The other

vehicles (LAV-AT, LAV-$C^2$, LAV-L, LAV-M, and LAV-R) use a single bolted-in plastic fuel tank on the left rear sponson. Dual fuel pumps in the fuel tank move the fuel to the engine. The fuel flow is identical to the M113-series vehicles after the fuel passes the delivery and return couplers (see Figures 10 and 11 in Addendum).

## 5.3. Fuel Information And Comparison

### 5.3.1. Definitions.[17]

- Flash Point: The lowest temperature at which the vapors from a petroleum product will ignite momentarily (i.e., flash) on application of a flame under specified conditions (ASTM Method D56). NOTE: The flash point is the first point of the flammability limit (the intersection of the lean limit and vapor pressure curves in Figure 5-2). Significance: Fuels with a flash point below normal operating temperature can form a potentially explosive fuel-air mixture in the ullage.

- Autoignition Temperature: The temperature at which a petroleum product will spontaneously ignite in the absence of a flame under specified conditions (ASTM Method D2155). Significance: Fuels should not be exposed to temperatures in excess of this. No ignition source (e.g., a spark) is necessary for combustion to take place above the fuel's autoignition temperature.

- Ambient Combustion Temperature: The flame temperature achieved during burning (pool fire) of a fuel. Significance: The lower the ambient combustion temperature, the less energy released, and thus less likely the burning fuel is to ignite other combustible items.

- Vapor Pressure: The pressure exerted by a product under specified test conditions (ASTM Method D323) due to its tendency to vaporize. Significance: Vapor pressure is a measure of volatility. A fuel with a higher vapor pressure, at given conditions, will evaporate at a faster rate (more volatile). The gaseous state requires the minimum energy for ignition.

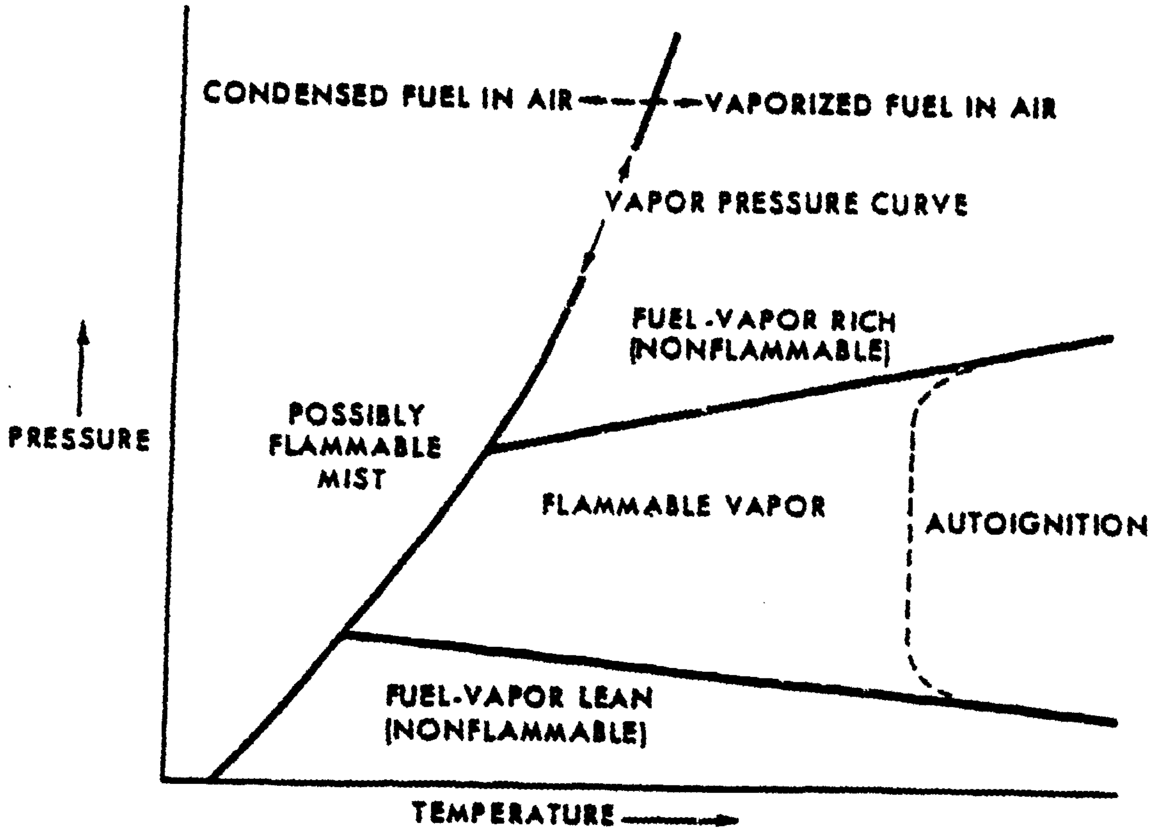



Figure 5-2. Flammability Characteristics of a Combustible Vapor in Air

- Fuel Electrical Conductivity: The measure of a fuel's ability to conduct electricity. Significance: Conductivity determines the rate of static charge buildup/dissipation. The primary source of static charge is high refueling rates. Higher conductivity will dissipate static charge before buildup reaches an unsafe level. Discharge of static electricity can ignite a combustible fuel-air mixture. Additives are used to increase fuel conductivity.

- Pour Point: The lowest temperature at which a liquid will flow (or pour) in a specific test (ASTM Method D97). Note: The pour point is used herein because it is what MIL-HDBK-114 uses to describe the lowest usable temperature of a fuel. The Belvoir Materials, Fuels and Lubricants Laboratory uses the cloud point to more accurately measure fuel usability in diesel engines. The Air Force uses the freeze point to relay similar information for jet engines. The freeze point, pour point and cloud point of a fuel are usually within a few degrees of each other (2 to 10 degrees). Significance: The lower the pour point/freeze point/cloud point is the more usable the fuel is at low temperatures.

- Heat of Vaporization: The amount of energy required to evaporate a unit quantity of a substance at a given temperature and pressure. Significance: The higher the heat of vaporization, the more energy that is required to release vapors and sustain combustion. This will determine whether combustion will be self-sustaining or will require outside energy input to continue. If outside energy is necessary, the fire will self-extinguish without it.

5.3.2. Fuel Types

- Diesel Fuel (VV-F-800) is the primary fuel for compression ignition engines and turbine engines (e.g., M-1 Tank). Diesel fuels are referred to as middle distillates and have a boiling range higher than gasoline. The various grades of diesel may be blended with kerosene to reduce fuel waxing problems. Four grades are available: DF-2 (CONUS), DF-2 (OCONUS), DF-1 (winter), and DF-A (arctic). The colder climate grades (DF-A and DF-1) are more volatile than DF-2 and have lower operating temperature limits.

- Automotive Gasoline (VV-G-1690) and Combat Gasoline (MIL-G-3056), known as MOGAS, are the primary fuels for spark ignition engines and have no current use in U.S. Army combat vehicles. Use is restricted to automobiles and older tactical vehicles. MOGAS is extremely volatile and presents a severe fire hazard in the combat environment. Several grades are available, but no significant fire hazard differences exist among the different grades.

- JP-4 (MIL-T-5624) is the primary fuel for Army and Air Force turbine-powered aircraft. JP-4 is less volatile than MOGAS, but still presents a fire hazard. It is preferred for aircraft use due to its high energy content per pound, low temperature limits, minimum smoke and carbon deposition, and low flame luminosity. Note that JP-4 is considered too hazardous by commercial airlines, and therefore, is not used by the civilian sector.

- JP-5 (MIL-T-5624) is the primary fuel of Navy aircraft, particularly on aircraft carriers. It is a kerosene blend developed to minimize the fire hazard associated with lower flash-point fuels. Its low temperature limit is higher than JP-4. Availability is limited due to the extensive refining necessary.

- JP-8 (MIL-T-83133) is currently used by the USAF in the U.K. Diesel fuel is blended with JP-8 for winter use in Europe. The properties of JP-8 are similar to the diesel fuels. JP-8 is very similar to JET A-1, commercial aircraft turbine engine fuel. JP-8 is currently being made available in European NATO countries.

Table 5-2 is a comparison of the combustion characteristics defined above for several commonly used DOD fuels.

The data in Table 5-2 indicates that all fuels would ignite when exposed to shaped charge weapon temperatures (3,000°F to 5,000°F) given the correct fuel-air mixture. However test results have shown that the probability of a sustained fire resulting from ballistic attack is directly related to the fuel temperature with respect to its flash point. As the fuel temperature increases, the probability of a sustained fire increases. As the fuel approaches its flash point, the probability of a sustained fire approaches unity. The spall created from aluminum armor penetration

Table 5-2. Characteristics of Commonly Used DOD Fuels

| Fuel Characteristic | DF-2 | DF-1 | DF-A | MOGAS | JP-4 | JP-5 | JP-8 |
|---|---|---|---|---|---|---|---|
| Flash Point Temperature (°F) | 125 min | 100 min | 100 min | -50 to -36 | -10 to 30 | 140 min | 100 min |
| Autoignition Temperature (°F) | 437 | 467 | 480 | 536 | 475 | 460 | 450 |
| Ambient Combustion Temperature (°F) | 850 to 900 | 850 to 950 | N/A | 1700 to 2000 | N/A | N/A | 900 to 950 |
| Vapor Pressure (psi at 100°F) | less than 1 | less than 1 | 0.5 ‡ (to 3) | 7 to 9 | 2 to 3 | 0.5 ‡ (to 3) | less than 1 |
| Fuel Electrical Conductivity (pS/m) | 0 to 10 | 0 to 100 | 0 to 100 | 20 to 80 | 200 to 600 | 200 to 600 | 200 to 600 |
| Pour Point "low use" Temperature (°F) | -10 † max | -40 † max | -70 max | -76 max | -72 § max | -51 § max | -53 § max |
| Heat of Vaporization at 72°F (cal/g) | 61.6 | 48.6 | N/A | 18.6 | N/A | N/A | 34.4 |

‡ dependant upon the fuel, blended as needed. May be found locally as high as 3 psi.

† Reported as the cloud point.

§ Reported as the freeze point.

N/A - No data available

See references 18 19 20 21 22 23 24.

provides a better ignition source than from steel armor.[25] Therefore fuels that are below their flash points will be more difficult to ignite and offer an advantage. Hence, the change from MOGAS to diesel fuel was done years ago.

The ambient combustion temperatures show that MOGAS should be avoided because of its much higher flame temperature and, therefore, much higher energy level which can easily start other materials burning.

The vapor pressure data show that JP-4 and MOGAS readily produce vapors at standard temperature and pressure (72°F and 1 atm.), DF-A and JP-5 moderately produce vapors and DF-2, DF-1, JP-5, and JP-8 do not. Hence, DF-2, DF-1, and JP-8 are the safer fuels with respect to fuel fire prevention under standard conditions.

Fuel electrical conductivity of the jet fuels is greater than that of the diesel fuels. However, this is controlled by additives to compensate for the high refueling rates (600 gallons per minute) used for combat aircraft. Current refueling rates for ground combat vehicles are much lower (12 to 45 gallons per minute) and buildup of significant static electrical charge does not occur. If ground combat vehicles were refueled at more than 200 gallons per minute, safety regulations would require additives to the diesel fuel as well, making the diesel fuel as resistant to static discharge as the jet fuels.

The pour point reported in Table 5-1 is approximately the lower usable temperature limit of that fuel. Aircraft operate from sea level to 40,000 feet and higher and require a fuel which remains pumpable under wide temperature extremes. Ground combat vehicles are required to operate over an ambient temperature range of minus 25 to 125 degrees fahrenheit and storage from minus 60 to 160 degrees fahrenheit. The base fuel(s) can be blended locally to meet the requirements of the local climate.

Note that JP-8 has a heat of vaporization half that of DF-2. Even though the boiling temperatures are about the same, a given amount of JP-8 requires less energy to vaporize than the same amount of DF-2. This means that JP-8 will produce more vapors in air with less energy input than DF-2 at the same temperature. The effect is somewhat counteracted by the slower kinetics of JP-8 to absorb heat over DF-2. (The heat capacity of liquid JP-8 is greater than DF-2.) JP-8 takes more time than DF-2 to absorb the

same amount of energy, which partially counteracts its lower heat of vaporization.

The logistics of joint operations of aircraft and ground vehicles requiring two different fuels is undesirable. Therefore, the Department of Defense (DOD) has recently initiated a one fuel forward concept involving use of JP-8 for all ground combat vehicles as well as aircraft in Europe.[26] The switch from JP-4 to JP-8 for aircraft would offer a significant fire survivability improvement. The switch from diesel fuel to JP-8 for ground vehicles, however, should not significantly affect fuel fire survivability. Currently, NATO countries have JP-8 under test. JP-8 has NATO approval to be the primary ground vehicle fuel. The diesel stocks stored in Europe will be used until depleted, then JP-8 will be used. The Belvoir Research, Development, and Engineering Center, which has Army responsibility for fuels and lubricants, has evaluated both diesel and JP-8 fuels over many years and has concluded that JP-8 will offer no change to fuel fire safety and may reduce the level of combustion by-products.[27]

## 5.4. <u>Aircraft versus Ground Combat Vehicle Fuel Fire Survivability</u>

Aircraft and ground combat vehicles share little in common other than the use of a hydrocarbon fuel for propulsion and operation in a hostile environment. The primary differences between aircraft and ground combat vehicle fuel fire survivability include the threat encountered on the battlefield, the design and protection of the fuel system, and the fuels used.

### 5.4.1. Threat.

- The threat to aircraft is predominantly in the 20-30mm range and of the high explosive incendiary type. These rounds can easily penetrate the thin skins of aircraft and their fuel tanks. The incendiary characteristic of these rounds contributes to the probability of an explosion and/or fire occurring. The impact of the round can also inflict considerable damage to the fuel tank through hydraulic ram. Larger threats, such as air-to-air missiles, are so destructive that a fuel fire after impact is of secondary concern.

- Threats similar to aircraft threats exist for ground combat vehicles. However, only lightly armored

vehicles and externally mounted fuel tanks (e.g., M113, M113A2) are subject to penetration by these threats. Much larger threats, on the order of 115-125mm, are targeted at ground vehicles and are capable of penetrating several hundred millimeters of conventional armor. Ground vehicles are also exposed to land mines, artillery rounds and overhead attack weapons. The armor of a main battle tank may not protect a fuel tank due to the extreme damage occurring when a large round passes through. Figure 5-3 shows an M60A3 fuel tank after penetration by a large-caliber projectile. Damage from hydraulic ram will also occur due to the projectile penetration. However, due to the large vent area created, the severity of hydraulic ram is not much greater than with aircraft. Burning of pooled fuel outside of the fuel tank, not an explosion inside the fuel tank, is the primary fire concern with ground combat vehicles.

5.4.2. Fuel System Layout.

- Aircraft store fuel in all available locations, with the wing areas and rear fuselage the primary locations. Many of the fuel tanks are built integral with the airframe, acting as structural members as well. Fuel is not normally stored in the crew compartment and a fire wall separates nearby fuel from the crew. In most configurations, the fuel tanks and the crew compartment are not both in the path of a projectile. The possibility of entrained or leaking fuel entering the crew compartment is, therefore, low. Fuel tanks are interconnected to balance the fuel load. Isolation valves are available to isolate a fuel tank if it is ruptured. Fuel lines are routed away from crew areas whenever possible. Many high-pressure fuel and hydraulic lines are present with the attendant rupture and spray problems.

- Ground combat vehicles usually store fuel within the confines of the armor envelope. This does not, however, guarantee freedom from penetration. The probability is reduced, but the severity of the resulting fire after penetration is greater. The location of the fuel tanks within the armor envelope varies, but is generally as close to the engine and as low as possible. The fuel tanks sometimes protrude into the crew compartment with a separating barrier. Use of external fuel tanks is increasing

Figure 5-3. M60A3, Damage from 105 mm Kinetic Energy Penetration.

since stored fuel takes up valuable inside space and increases the armor protection required. Fuel lines are generally low pressure, however the M1-series with its turbine engine uses high-pressure lines.

5.4.3. Fuel.

- Air Force and Army aircraft use JP-4, a volatile fuel which provides good performance throughout all ambient temperatures. The primary problem with JP-4 is the formation of a combustible fuel-air mixture at low temperatures (minus 60°F and above). Navy aircraft use JP-5 which is a low volatility fuel, similar to diesel fuel in this respect. It is used exclusively by the Navy due to the extreme fire safety measures necessary on aircraft carriers.

- Currently, all ground combat vehicles use diesel fuel of one of three grades, DF-2 (normal), DF-1 (cold region), or DF-A (arctic). The primary difference is cold weather suitability with an inherent increase in volatility for cold weather use. Of note is the proposal to convert Europe based vehicles to JP-8, as discussed earlier.

## 5.5. Passive Inerting Systems

U.S. Air Force combat experience in Southeast Asia indicated that the fuel tanks on aircraft were one of the most vulnerable areas to attack. Therefore, a means for reducing the vulnerability of the fuel tanks to antiaircraft weapons was investigated. Several different passive inerting systems have been developed in response to this need. These passive inerting systems operate by altering the physical conditions within the fuel tank or surrounding area such that a fire cannot be initiated or propagate. These inerting systems are designed to continuously protect a vehicle by interfering with the start and/or growth of the combustion process. This can be done by maintaining an overly rich or lean fuel-air mixture, or physically or chemically interfering with the start or advance of the flame front. The specific methods which have been investigated include: fuel tank fillers, fuel tank ullage inerting, fuel tank jacketing, self-sealing fuel tanks, fire-resistant fuels, and overall fuel system design.

5.5.1. Fuel Tank Fillers. Fuel tank fillers are those materials which are installed in the interior of the fuel tank and are intended to physically interfere with the

combustion process in the ullage. Two types of fillers have been extensively tested: polyurethane reticulated foams and expanded aluminum. Several other materials have been proposed, including reticulated metal foam and nonwoven fabrics, but not evaluated for this application.

There are two primary operating mechanisms for fuel tank fillers: removal of energy from the combustion process by absorption of heat or by mechanical interference.[28] Both mechanisms reduce the transfer of energy from energetic molecules (i.e., molecules in the reaction) to non-energetic molecules (i.e., molecules not in the reaction). Absorption of heat is accomplished by the heat sink effect of the filler material. Mechanical interference is accomplished by the small "cells" in the filler blocking the flame front and dissipating energy.

To provide maximum protection, the material should fill as much of the fuel tank volume as possible. Some areas must be left unprotected, however, to allow clearance for ancillary equipment (fuel level instruments, fill ports, fuel pumps, etc.). With the maximum volume covered, the weight gain and fuel capacity losses in aircraft are considered unacceptable and have led to a technique termed "voiding." Voiding leaves selected areas unprotected to reduce the quantity of filler used. The amount of volume voided is dependent on the system characteristics and desired performance. The operating mechanism for voiding is to allow some pressure rise from combustion in the void areas, but to limit it to levels the fuel tank can withstand. The amount of voiding is termed as either normal (approximately 20% void volume) or gross (up to 70% void volume).[29]

The advantages of fuel tank fillers include:

- continuous protection
- unaffected by temperature or altitude
- compatibility with the fuels currently used
- slosh mitigation
- reduction of the effects of hydraulic ram.

The disadvantages of filler materials include:

- added weight

- loss of fuel capacity
- fuel retention
- unknown effects on fuel quality
- an increased maintenance burden when fuel tank repair or service is required.

5.5.1.1. Polyurethane reticulated foam. Polyurethane reticulated foam is a "plastic" material which is formed into an open cell (i.e., reticulated) foamed structure through the application of heat and pressure. Hydrogen is injected into the foam and exploded to open individual cells. Polyurethane reticulated foam can either be polyester or polyether type depending on desired physical characteristics. The material is covered under MIL-B-38054, "Baffle and Inerting Material, Aircraft Fuel Tank."

Polyester reticulated foam was first used by the Air Force for inerting fuel tanks and dry bays in the late 1960s. This foam (Type I per MIL-B-38054) has a relatively high nominal density of approximately 1.8 $lb/ft^3$, a reduction in usable fuel volume of approximately 5% (fuel displacement plus retention), and an average service life of 3 to 7 years. The density and service life were considered unacceptable and in the early 1970s improved polyester foams (Type II coarse pore and Type III fine pore) were introduced. The improved foams offered a 25% weight reduction (1.35 $lb/ft^3$) and an increased service life (5 to 8 years). The goal of a foam with a service life equal to the aircraft life was still desired, and in the late 1970s hybrid polyether foams (Type IV coarse pore and Type V fine pore) were introduced which met this goal. A significant drawback to these foams is an electrical conductivity approximately one-tenth that of the polyester foams. In use, static charge will accumulate during refueling or operation and periodically discharge. The discharge can ignite the ullage vapors, damaging the foam and the aircraft. In the early 1980s treated polyether foams (Type VI coarse pore and Type VII fine pore) were introduced which have a long service life plus offer conductivity 10 to 100 times greater than the polyester foams.[30] These latest configurations offer minimal weight penalties, resistance to static charge buildup and an extended service life. The effectiveness of these materials in controlling aircraft fuel fires initiated by small-caliber projectiles is well documented.[31 32 33 34]

Regardless of aircraft experience, use of reticulated polyurethane foams in ground combat vehicles will offer little or no significant benefit. The primary reason being that a combustible fuel-air mixture is not normally present in the ullage of a diesel fuel tank. Limited testing has supported this. Hoge found that polyurethane foam in the fuel tanks of the M113 and M113A1 offered no fire survivability improvement.[35] The foam actually increased the severity of the fire. It was surmised that the capillary action of the foam led to wicking of the fuel and a more severe fire. Copland found that when rounds larger than 14.5mm were used polyurethane foam did not provide any worthwhile protection.[36] Romanell found that reticulated polyurethane foam offered no reduction in fire severity in an M113 external fuel tank.[37] Zabel found that the use of reticulated foam in the fuel tank of the advanced survivability test bed vehicle (an M2 based vehicle) showed no distinct advantage to justify its use.[38]

Polyurethane reticulated foam is currently installed in the Army's M110 Self Propelled Howitzer. Due to the large-caliber (8-inch) projectiles fired, this vehicle has experienced severe fuel slosh problems. The foam is used in the fuel tanks to mitigate fuel slosh and support the fuel bladder. The foam was not intended, nor has it been tested for, reduction of fuel fire severity in this application.[39]

5.5.1.2. Expanded aluminum. Expanded aluminum is represented by a proprietary product known as Explosafe, a product of Vulcan Industrial Packaging Ltd.. It is made from aluminum alloy foil 0.015 to 0.030 inch thick which is slit and expanded to a hexagonal mesh configuration. The foil mesh batts are then cut and shaped to fit the fuel tank. The resulting material is an open cell structure which performs similarly to coarse pore polyurethane foam. The physical characteristics of Explosafe are a density of 2 $lb/ft^3$, and fuel displacement of approximately 3%. The primary enhancement, like reticulated polyurethane foam, is to suppress the overpressure resulting from fuel tank penetration (i.e., hydraulic ram and/or explosive combustion of the ullage). This material has excellent electrical conductivity, offers an indefinite service life, and is free of operating temperature limitations. The material is covered by MIL-B-87162.

Test results with Explosafe have been mixed. Copland found that the Explosafe appeared to intensify the effects of hydraulic ram when tested in 5-gallon cans with diesel fuel

and gasoline.[40] The mechanism surmised for this occurrence is as follows: the projectile, as it passes through the Explosafe, becomes entangled and pulls the material along. When this mass (projectile plus Explosafe) strikes the far wall of the fuel tank, the resulting damage is worse than that caused by the projectile alone. Braadfladt found that Explosafe offered no significant increase in survivability when an M113 internal or external fuel tank was subjected to shaped charge attack.[41 42]

Vikestad and Schaekel found that Explosafe offered mixed results when striking the liquid portion of the fuel tank, in some instances reducing the size of the fireball, in other instances increasing it.[43] When striking the ullage, there was no significant benefit from the Explosafe. It was noted that when struck, the damaged Explosafe leaves particles of aluminum which could be drawn into the fuel system, resulting in damage. They also investigated the heat-sink effects of Explosafe and found it offered no heat-sink advantage and may actually increase the rate of fuel tank heating.

Hogan and Pedriani found that when Explosafe was evaluated in a flame tube setup for combustion overpressure, it performed better than a similar density coarse pore polyurethane reticulated foam.[44] Pedriani found that 100-gallon aircraft wing tanks were not sensitive to ullage explosions when Explosafe was installed.[45] They also found that due to the relatively large spacing of the cells, the advancing flame front of explosive combustion will only be slowed, not stopped.

The Marine Corps evaluated Explosafe for its assault amphibious vehicles and stopped testing because of three primary problems: the kit consisted of many pieces and installation was extremely complicated, the Explosafe interfered with the functioning of the forward and rear fuel pumps, causing them to cavitate due to fuel starvation, and the Explosafe did not reduce the risk of fuel fires when the fuel tank was punctured by a large projectile.[46] For the same reasons as reticulated polyurethane foam, expanded aluminum is considered ineffective for ground combat vehicles. Explosafe is not used in any production U.S. military combat vehicle.

5.5.1.3. Other materials. Several other materials have been proposed for use in fuel tank inerting. However, they have had little or no testing for this application. The materials include metal or metallized foam, nonwoven fabrics, and rigid foams.

- Metal or metallized foams are formed similar to polyurethane reticulated foam. A representative product of this type is Duocel, a product of Energy Research and Generation, Inc. The base stock, in this case aluminum, is subjected to heat and pressure to form the reticulated structure. Unlike the polyurethane foam, however, the resulting structure is rigid and cannot be compressed without damage. The rigidity is such that the material can be used as a structural member with good energy absorption properties. This material, like expanded aluminum, has good electrical conductivity, offers an indefinite service life, and is free of limitations on operating temperature. A disadvantage to this material, however, is due to its rigidity; installation can be done only at the time of fuel tank manufacture and access to the fuel tank interior for maintenance or repair would be very difficult. Because of this and its higher density, metal foam has not been tested or extensively evaluated by the military for fuel tank inerting. It is a product used in the aerospace industry which has been proposed based on its limited similarity to polyurethane foam. In light of the installation and service problems, and the more important consideration that ground combat vehicles do not have an ullage explosion problem, investigation of this material is not recommended.

- Nonwoven fabrics are represented by a family of materials manufactured by 3M Corporation. The basic configuration of this material is a bonded fibrous, low-density, flexible and resilient nonwoven structure. The material has been touted as exceeding the performance of the polyurethane foams in terms of chemical resistance, fuel flow properties, and higher temperature capability. Botteri found that in flame tube tests the nonwoven material offered better performance than Type I reticulated polyurethane foam.[47] Malmberg and Wiggins found that the nonwoven material offered better performance than the foams.[48] Further testing of the material has not been pursued.

- Rigid foams are not intended for use as fuel tank fillers, but are used to fill void areas in aircraft dry bays in the vicinity of fuel tanks. The material fills the empty spaces where a fuel-air mixture could accumulate and attenuates hydraulic ram, which would be transferred to the aircraft

structure. The foam can be installed by foaming in place or by fabricating pieces which are installed during assembly. Due to its insulating properties, it can protect the fuel tank from exterior fires and can act as a flame barrier for other compartments. This material has limited application in ground combat vehicles since all available space is used, and any void areas are used for the crew or passage of cooling air. Zabel evaluated rigid foam as a buffer material around ground combat vehicle fuel tanks, and found that the foam contributed to ballistic penetrator breakup, causing larger entrance and exit holes in the fuel tank than otherwise encountered.[49] Romanell found that rigid polyurethane foam panels attached to the exterior wall of an external fuel tank on an M113 offered no reduction in fire severity.[50] The only current Army ground vehicle application for this type of material is as a part of the "swim" kit to increase the buoyancy of M113-series vehicles when additional armor is applied.

### 5.5.2. Ullage Inerting Systems

Ullage inerting systems are intended to prevent explosive combustion in the fuel tank ullage or aircraft dry bays. The system maintains either an oxygen deficient mixture (e.g., addition of an inert gas) or a fuel rich mixture (e.g., addition of fuel vapor). The methods for doing this include inert gas, engine exhaust, extinguishing agent addition and fuel fogging. These systems in all forms are generally ineffective in a ground combat vehicle application because diesel fuel (and JP-8) does not form a combustible fuel-air mixture under normal operating conditions (the mixture is normally too lean for combustion). Descriptions of several systems are provided, however, none of the following specific ullage inerting systems are recommended for application to ground combat vehicles.

Inert gas is the most common type of ullage inerting system and is used in several aircraft applications. The basic operating principle is to supply an inert gas, usually nitrogen ($N_2$) or carbon dioxide ($CO_2$), into the ullage or dry bay. The inert gas dilutes the available oxygen such that insufficient oxygen is available for combustion or severely limits overpressure if combustion occurs. Dilution of oxygen to approximately 10% by volume has been accepted as the minimum required dilution level. This was verified by Ferrenberg in extensive testing using 23mm high

explosive incendiary projectiles fired into JP-4 filled fuel tanks.[51] While both $CO_2$ and $N_2$ have been successfully used for fuel tank inerting, logistics and economics tend to favor $N_2$. The source of the inert gas can be either a liquid (cryogenic) supply or an onboard generator. Liquid supplies have weight, space and logistical penalties. Onboard generators separate the more permeable constituents of air (including oxygen) from the less permeable gases (primarily $N_2$). This results in an essentially inert gas that is used to protect the ullage. The generators require no regular resupply of expendables. Onboard generation is the preferred method for large volumes.[52 53]

The engine exhaust method of inerting operates by pumping vehicle exhaust gases (oxygen depleted due to combustion) into the ullage. The gases must be cooled and filtered before injection into the fuel tanks to prevent ignition or deposition of particulates in the fuel tanks. This type of system is best suited for large fuel tanks and low speed exhaust. The primary application is in fuel tankers. Turbine engines have such high exhaust flow rates and temperatures that application of this method is prohibitive.

Extinguishing agent inerting is accomplished by pumping gaseous extinguishing agent into the fuel tank ullage. The extinguishing agent preferred is a Halon that is normally in the gaseous state (e.g., 1301). This system can have a problem with the extinguishant gas dissolving into the liquid fuel, as is the case with Halon 1301, and decreasing engine performance and/or creating toxic by-products during combustion.

Fuel fogging, unlike the inerting methods above, maintains a fuel rich condition in the ullage by employing some of the liquid fuel itself in the form of a fog. The fuel fog system works on the principle that finely divided liquid fuel acts as if it were in the vapor state, adding to the natural fuel vapor concentration, thereby driving the ullage over-rich. Wiggins and Malmberg found this method to be ineffective, however, due to the inability to maintain a sufficiently rich mixture over the full operating temperature range.[54] Pedriani found that a condensate-formed fuel fog system was effective in preventing ullage explosions caused by an electric match, but ineffective in preventing fires initiated by an incendiary gunfire simulator.[55]

5.5.3. Fuel Tank Jacketing. This method of inerting consists of placing a self-contained jacket on the outer surfaces (all or part) of the fuel tank. When the application permits (e.g., a new vehicle design) the jacket can be designed as an integral part of the fuel tank. The jacket is filled with a fire extinguishing agent (e.g., water, Halon, purple K, etc.) which can be either a liquid, gas, gel or solid (flake). The extinguishant is released when a projectile penetrates the jacket. As the projectile penetrates, it draws the extinguishant along the path of the projectile. Mixing of the extinguishing agent with the fuel spray will occur and prevent, or reduce the intensity of, fuel combustion. The jackets will also give added support; the jacketed fuel tank will suffer less damage from hydraulic ram. This can provide a fuel tank that will release a minimum of fuel after penetration. The effectiveness of the jacket is determined by the construction of the jacket and the extinguishing agent used. The jackets are most effective, however, against ignition of fuel by the incendiary effects of the penetrating projectile. Deposition of fuel on a hot surface may still lead to ignition, depending on the characteristics of the extinguishing agent used.

Pedriani evaluated the use of a fire extinguishing powder within a honeycomb structure on the surface of a helicopter fuel tank.[56] Using a 0.1-inch-thick panel filled with dry powder extinguishant, the design successfully prevented a fire when the fuel tank and panel were penetrated by small-caliber munitions. Finnerty evaluated jackets (powder packs) in a ground combat vehicle scenario (simulating the M992 FAASV).[57] In this case, the hydraulic reservoir was considered a greater fire threat to the crew than the fuel tank. In conjunction with the jackets, a containment structure was constructed around the reservoir to minimize fluid spray. For these tests a powdered extinguishing agent (Monnex) was used. When tested against a medium shaped charge, 1-inch-thick jackets demonstrated a reduction in fire-out times of approximately 50 percent when compared to similar tests without jackets. Zabel evaluated several extinguishing agents in prototype external fuel tanks for the M2 Advanced Survivability Test Bed (ASTB) vehicle.[58] Water, mixtures of water and foaming agents, Purple K (potassium bicarbonate with a coloring agent), monoammonium phosphate (MAP) and bromochloromethane (Halon 1011) were evaluated. The fuel tanks were a new design with integral jackets. Testing indicated that plain water, purple K and Halon 1011 were effective in reducing fireball intensity and extinguishing any resultant fires in less than 100 milliseconds. The

water mixtures and the MAP were not as effective, and were not recommended for use as tested.

5.5.4. Self-Sealing Fuel Tanks. MIL-STD-5578 reflects the current technology available for fuel tank materials which can provide a self-sealing action. The largest hole the specification tests the self-sealing materials against is about three quarters of one inch. The self-sealing of holes larger than this is not a requirement. The 3/4-inch hole is small when compared to the 5-inch diameter or greater hole produced by an antitank munition penetration. Further, testing is restricted to kinetic energy projectiles which do not produce any significant amount of heat. A shaped charge can generate temperatures in excess of 5,000°F which will vaporize the plastic or rubber such that self-sealing is not possible. Additionally, projectile impacts which hit a structural member or a corner of the fuel tank are eliminated from the specification test due to the catastrophic failure which occurs when these areas are hit. Therefore, until the technology of seal-sealing fuel tanks develops to the point where the penetration hole from an antitank munition can be effectively sealed, self-sealing fuel tanks will not be effective in the ground combat vehicle environment.

5.5.5. Fire-Resistant Fuels (FRF). The previously discussed inerting methods have all dealt with secondary conditions affecting combustion of the fuel. The primary factor affecting combustion is the fuel itself. This inerting method chemically alters the fuel such that it will not burn or will quickly self-extinguish. The act of making the fuel noncombustible is not difficult; however, doing this while maintaining its capacity as a motor fuel is very difficult. This has been the primary goal of the Army's Fire-Resistant Fuel program. The Army began investigating FRF in the early 1960s as a means of reducing fire vulnerability in aircraft. Development has passed through six generations of FRF. The first four generations were directed towards aircraft fuels, while the fifth and sixth generations of FRF were diesel fuels.[59]

The first generation of FRF was formulated so that fuel gelling occurred just prior to hazard occurrence. This FRF was investigated from 1964 to 1966. The fuel was a normal pumpable liquid until a projectile penetrated the fuel, which would initiate an irreversible chemical change of the fuel to a gelled state. This technique was not considered viable and the investigation was stopped.

The second generation FRF was a semisolid, but pumpable, fuel and water emulsion. This FRF was investigated from 1965 to 1970. The fuel appeared solid-like until exposed to high shear stresses (e.g., pumping), then the fuel reverted to a pumpable liquid. This technique was also considered not viable and the investigation stopped.

The third generation FRF was a viscous-liquid, fuel and water emulsion. This FRF was investigated from 1969 to 1972. This fuel eliminated the pumping problems of semisolid fuels, but had serious performance disadvantages. This fuel was also considered not viable and the investigation stopped.

The fourth generation FRF is formulated with high molecular weight polymeric additives for inhibition of mist formation and has been investigated since 1971. The additive prevents the fuel from creating a mist, which is necessary to be able to initiate and maintain combustion for diesel fuel. This technique has been successfully demonstrated, but currently cannot be economically fielded.

The fifth generation FRF was the first to use diesel fuel as the base fuel and was formulated with a volatile halogenated fire extinguishant as a fuel constituent. This FRF was investigated from 1972 to 1976. The addition of Halon extinguishing agent provided self-extinguishing of pool burning. This fuel was not further investigated when fuel system corrosion and toxic exhaust by-products were identified.

The sixth generation FRF is a nonviscous, fuel and water emulsion. This FRF has been investigated since 1976. This fuel self-extinguishes through the absorption of heat by the water. This fuel was planned for fielding through BRDEC. However, logistical constraints and low-temperature decomposition of the emulsifier were encountered. Investigation was subsequently stopped.[60]

Other forms of fuel conditioning have also been evaluated. Kanakia and Wright considered fuel temperature and antimisting additive concentration.[61] Fuel cooling alone showed no benefit in fire vulnerability reduction. Fuel cooling accompanied by a high concentration of antimisting agent, however, showed potential for preventing pool fires and reducing mist fireballs. The net result was that this antimisting additive was not effective in reducing pool fires when the bulk fluid temperatures were near or above the fuel flash point.

Overall the FRFs have demonstrated excellent fire resistance; however, the attendant logistic complications currently make them not fieldable.[62 63] The Army effort to field an FRF is currently on hold.

5.5.6. Fuel System Design. Proper fuel system design can prevent many of the situations which lead to a fuel fire, or limit the severity of any resultant fuel fire. The most appropriate time for improvements is in the vehicle design stage. To assist designers in the techniques available for fuel system design, the Army is preparing two design handbooks to organize and consolidate documentation on technologies and techniques available to improve ground vehicle designs. The handbooks cover fuel system design and fire survivability.

The "Fuel System Design Guide for Military Vehicles" includes the following directions for fuel tanks:

- provide a safety venting system to prevent internal tank pressure from rupturing the fuel tank in the event it is subjected to a fire.

- require a minimum 5% ullage volume at maximum fill.

- use baffles to reduce fuel sloshing.

- provide a non-spill operational vent to release air and other gases so that combustible mixtures do not form.

The "Design Handbook for Fire Survivability of Combat Vehicles" discusses:

- the types of combat vehicle fires.

- the materials used in combat vehicles and the fire hazards they present.

- the principles of fire prevention in combat vehicles.

- the criteria for insuring crew survivability.

- the technology available for detection and extinguishing of fires in combat vehicles.

- the test and evaluation methods available for design verification.

Zabel demonstrated that covering the engine compartment bilge will greatly reduce the severity of the fires by restricting the availability of oxygen to a pool fire in the bilge.[64] The entire bilge should be covered to restrict the passage of air. The cover should not be liquid tight, however, to allow spilled fuel to collect beneath it. Zabel also demonstrated that fuel tanks can survive the hydraulic ram of a ballistic impact and will not rupture catastrophically if the fuel tank is confined within its elastic limits.

External fuel tanks have been shown to be a very effective design technique to reduce ground combat vehicle damage from fuel fires. An inherent drawback to this approach however, is that the external tanks expand the vehicle envelope, thereby making it a larger target. Extensive testing has been conducted, and external fuel tanks have been fielded on several Army and Marine Corps ground combat vehicles. When the fuel tank is penetrated, most of the fuel is dumped outside of the vehicle, thereby preventing a severe internal fire.[65 66] A spacer between the fuel tank and the vehicle will further reduce the amount of entrained fuel that is sprayed into the vehicle. Zabel showed that the effects of a 3.5 inch shaped charge penetration of an external fuel tank and the vehicle crew compartment can be reduced to safe levels with the following simple modifications:[67]

- placement of a gravel-filled, 3-inch-thick spacer between the external fuel tank and the hull.
- placement of a 2-inch thickness of a quenching agent inside the hull opposite the fuel tank.
- compartmentalizing the inside of the hull and using a ballistic fabric cover.

Finnerty analyzed ground combat vehicle fuel systems and provided the following guidance for fuel system design.[68]

- Design fuel flow systems to minimize the rise of fuel temperature as the engine operates. Use fuel system designs that produce no more than a 20 degree temperature rise above ambient. Reason: The higher the fuel temperature, the more flammable the fuel is.
- Isolate fuel tanks from the crew compartment and sensitive equipment. Reason: To use distance and barriers as protection.

- Use multiple fuel tanks. Reason: Permits only a partial loss of total vehicle fuel, retaining the fuel remaining in other fuel tanks.

- Use redundant fuel supplies to the engine. This requires a fuel pump in each fuel tank. Reason: Redundant fuel supplies reduce the required cascading of fuel from one fuel tank to another to feed the engine. Redundant fuel supplies permit bypassing damaged fuel tanks and using fuel directly from tanks which are not damaged.

- Incorporate fuel shut-off valves between each tank. Reason: Permits the "sealing off" or isolation of the damaged fuel tank. This prevents the draining of other fuel tanks through the hole in the damaged tank.

- Use fuel tank designs that reduce the damage from hydraulic ram. Reason: To keep the fuel tanks from splitting apart during munition impact. Fuel tanks should be designed to absorb or vent high internal pressures caused during munition impact such that most of the fuel will be retained. Adequate ullage is considered a necessary part of designing to alleviate damage from hydraulic ram.

- Do not use fuel tank materials or materials in the vicinity of fuel tanks that are easily ignited, pyrophoric, or "self-oxygenating." Use materials and construction that will not support combustion. Reason: To prevent creating an uncontrollable fire and to ignite as little combustible material as possible following munition penetration.

## 5.6. Foreign Technologies

- Israel: They do not use a system of fuel tank inerting for any of their ground combat vehicles per TACOM liaison officer.

- Federal Republic of Germany: They do not use a system of fuel tank inerting for any of their ground combat vehicles per TACOM liaison officer.

- United Kingdom: They do use a system of fuel tank inerting for selected equipment, mostly aircraft. Their system is a conjunction of rigid and reticulated foam as discussed above. The rigid foam used external to the fuel tanks is known as Atomel

and the soft foam used internally is known as Promel.

- Canada: Polyurethane reticulated foam has been installed in the Canadian Army Iltus jeep fuel tanks.

- Korea: Has U.S. designed ground combat vehicles - none of their own passive inerting technology.

LIST OF REFERENCES

1 Congressional Record, House Number H-10377 (November 17, 1987)

2 Finnerty, Anthony E., "Extinguishing Ammunition Fires," Report ARBRL-TR-02410, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (July 1982)

3 York, Emil J., "Non-Flammable Hydraulic Fluid for Armored Family of Vehicles (AFV)," U.S. Army Belvoir Research, Development and Engineering Center, STRBE-VF, Fort Belvoir, VA (28 October 1987)

4 U.S. Army, "Policy Statement on the Use of Monobromotrifluoromethane ($CBrF_3$ ) Suppressant as a Fire Extinguishing Agent," U.S. Army Material Command, Washington, DC, AMCTC No. 6704 (Approved 6 March 1969)

5 Sanderson, T. Ellory, "Final Report Special Study of M60A3 Automatic Fire Extinguishing System (AFES)," TECOM Project No. 1-VC-080-060-154, Report No. USACSTA-6564, U.S. Army Combat Systems Test Activity, Aberdeen Proving Ground, MD (August 1987)

6 Sokolis, Bernard A., "Final Report Comparison Test of M992 Field Artillery Ammunition Support Vehicle (FAASV) with Automatic Fire Extinguisher System (AFES)," TECOM Project No. 2-VS-100-ASV-017, Report No. USACSTA-6598, U.S. Army Combat Systems Test Activity, Aberdeen Proving Ground, MD (October 1987)

7 Miller, John E., "Final Report Preproduction Test of Automatic Fire Extinguisher System (AFES) for the Field Artillery Ammunition Support Vehicle (FAASV)," TECOM Project No. 2-VS-100-ASV-004, Report No. USACSTA-6193, U.S. Army Combat Systems Test Activity, Aberdeen Proving Ground, MD (May 1985)

8 Swanson, Dennis R., First endorsement to letter, "Clothing Protection for Skin Burn," HQDA (DASG-PSP-E) (21 April 1987)

9 per TACOM Israeli liaison officer - verbal (April 1988)

10 Zabel, P. H., and White, R. E., "Hydraulic Ram Study," Southwest Research Institute (SwRI) IR Project No. 06-9360, San Antonio, TX (December 1985)

11 Copland, Allister, "Hydrodynamic Ram Attenuation," Memorandum Report ARBRL-MR-03246, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (February 1983)

12 Copland, Allister, "Ballistic Evaluation of Fuel Cells for the LVT7 Family of Amphibious Vehicles," Report No. ARBRL-MR-03302, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (August 1983)

13 Zabel, Patrick H., "Test Program to Demonstrate Enhanced Survivability of Armored Aluminum Vehicle Fuel System to Shaped Charge Attack," Southwest Research Institute Project No. 06-8899, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (31 July 1986)

14 Hackenbruch, Douglas J., "Cost-Effectiveness of External Fuel Tanks for M113 Family of Vehicles," Report No. 79-04, U.S. Tank Automotive Research & Development Command, DRDTA-V, Warren, MI (June 1979)

15 Hackenbruch, Douglas J., "Cost Effectiveness of Automatic Fire Extinguishing System on the M60 Series Combat Vehicles," Report No. 79-04A, U.S. Army Tank Automotive Research and Development Command, DRDTA-V, Warren, MI (October 1979)

16 Ricketson, Darwin S., Segraves, Jill M., and Sisk, Francis G., LTC, "Tracked Vehicle Fire Analysis: 1984 Update," USASC Technical Report No. TR84-2, U.S. Army Safety Center, Ft. Rucker, AL (June 1984)

17 Lapedes, Daniel N., "McGraw-Hill Dictionary of Scientific and Technical Terms", McGraw-Hill Book Company, NY, NY (1976)

18 Finnerty, Anthony E., "Predictions of Probabilities of Sustained Fires for Combat Damaged Vehicles," Report No. BRL-TR-2875, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (November 1987)

19 MIL-HDBK-114, "Mobility Fuels User Handbook," US Army Belvoir Research, Development, and Engineering Center, STREB-. , Ft. Belvoir, VA, (16 January 1984)

20 Perry and Chilton, "Perry's Chemical Engineer's Handbook," 5th ed., McGraw-Hill, NY, NY (1973)

21 US Army, "Flammability Characteristics of Distillate Fuels," Belvoir Fuels Research Facility (SwRI) No. 234, US Army BRDEC (June 1987)

22 Author unknown, "Fire & Explosion Manual: Accident Investigation," Factory Mutual Insurance (August 1973)

23 Rose, J. W., and Cooper, J. R., Text, "Technical Data on Fuel", 7th ed., McGraw-Hill, N NY (1977)

24 McKinnon, Gordon P. and Tower, Keith, "Fire Protection Handbook,"National Fire Protection Association (NFPA), 14th ed., Boston, MA (January 1976)

25 American Petroleum Institute, API Standard No. 2001, Chicago, IL (April 1984)

26 Department of Defense, Directive, "Fuel Standardization," Number 4140.43 (11 March 1988)

27 York, Emil J., STRBE-VF, Memorandum For: Commander, US Army Material Command, Attn.: AMCDE-WH, Alexandria, "JP-8 and Combat Vehicle Survivability" (23 May 1988)

28 Clodfelter, R. G., "Design for Survivability - Fuel, Propulsion, and Power," Air Force Aero Propulsion Laboratory, unnumbered report, (circa 1970)

29 Author unknown, Technical Memorandum, "Reticulated Foam Explosion Suppression Kits for Fuel Tank Survivability (Guidelines for Design, Fabrication, Installation and Testing)," ENFEF-TR-85-1 (March 1985)

30 Author unknown, "Qualification Report for Scottfoam Corporation Types VI and VII Beige CSF-204 Conductive Safety Foams," Report No. SF-225-58 (11 April 1986)

31 Reed, Thomas O., "USAF Experience with Polyurethane Foam Inerting Material," Report No. ASNJI-70-2 (May 1970)

32 Author unknown, "Gunfire Effectiveness and Environmental Suitability of Void Filler Materials," Report No. ASD-TR-74-34 (September 1974)

33 Wilt, Benjamin H., "Compatibility of Reticulated Foams in Typical Turbine Fuels with Currently Approved Additives," Report No. AFWAL-TR-80-4135 (September 1980)

34 Holten, Andre J., "AX Fuel Tank Vulnerability Evaluation Report," Report No. AFFDL-TR-74-55 (July 1974)

35 Hoge, George F., Letter, "Field Demonstration of Polyurethane Filled Tanks," U.S. Army Combat Developments Command, CDCCS-LV, APO, San Francisco, CA (15 November 1967)

36 Copland, Allister, "Ballistic Evaluation of Fuel Cells for the LVT7 Family of Amphibious Vehicles," Report No. ARBRL-MR-03302, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (August 1983)

37 Romanell, M. J., "Engineering Test of Automatic Halon Fire Suppression System for M113 Armored Personnel Carriers, Ensure No. 246, Final Report," Report No. APG-MT-3990 (April 1972)

38 Zabel, Patrick H.,"Survivability Enhancement of Advanced Survivability Test Bed Vehicle Given a Shaped Charge Hit Through the Engine Compartment Fuel Tank," Report No. ASTB-2 (31 July 1987)

39 per TACOM Systems Engineering Directorate (AMSTA-UCA) - verbal history.

40 Copland, Allister, "Explosafe: An Evaluation for Hydrodynamic Ram Attenuation," Report No. BLL IMR No. 738 (February 1982)

41 Braadfladt, C. P., "Ballistic Test of M113A1/A2 Internal Fuel Tank With and Without Explosafe," FMC Technical Report No. 3801 (March 1982)

42 Braadfladt, C. P., "Ballistic Test of M113A1/A2 Internal Fuel Tank (P/N 11678175) with Explosafe," FMC Technical Report No. 3802 (April 1982)

43 Vikestad, Walter S. and Schaekel, Forrest, "The Evaluation of Explosafe in Preventing Explosions of Fire in Truck Fuel Tanks," Report No. BRL-TR-2881 (December 1987)

44 Hogan, Thomas A. and Pedriani, Charles, "Flame Tube and Ballistic Evaluation of Explosafe Aluminum Foil for Aircraft Fuel Tank Explosion Protection," Report No. AFWAL-TR-80-2031 (April 1980)

45 Pedriani, Charles M., "Testing to Evaluate the Use of Explosafe in a 100 Gallon Wing Tank," Memorandum For Record, DAVDL-EU-MOS, (22 May 1978)

46 Chambers, G. K., Letter, "Evaluation of Explosafe Installed on Marine Corps Assault Amphibian Vehicle," U.S. Marine Corps, Tactical Systems Support Activity, Camp Pendleton, CA (19 April 1988)

47 Botteri, Benito P., Letter, "Evaluation of 3M Test Samples" (18 July 1967)

48 Malmberg, Q. and Wiggins, E, "Advanced Flame Arrestor Materials and Techniques for Fuel Tank Protection.", Report No. AFAPL-TR-72-12 (1972)

49 Zabel, Patrick H., "Test Program to Demonstrate Enhanced Survivability of Armored Aluminum Vehicle Fuel System to Shaped Charge Attack," Southwest Research Institute Project No. 06-8899, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (31 July 1986)

50 Romanell, M. J., "Engineering Test of Automatic Halon Fire Suppression System for M113 Armored Personnel Carriers, Ensure No. 246, Final Report," Report No. APG-MT-3990 (April 1972)

51 Ferrenburg, Allen J., "Fuel Tank Non-Nuclear Vulnerability Test Program," U.S. Air Force Aero Propulsion Laboratory, AFAPL/SFH, Report No. AFAPL-TR-74-83, Wright Patterson AFB, OH (February 1975)

52 Manatt, S. A., Buss, L. B., and Funk, A. F., "Design Criteria for Application of Membrane Nitrogen Inerting Systems to Army Aircraft Fuel Tanks," Report No. USARTL-TR-77-50, AiResearch Co. (December 1977)

53 Manatt, S. A., et al., "Advanced Merbrane Nitrogen Inerting for Large Helicopters," Report No. NWC TM 3831, AiResearch Co. (August 1980)

54 Wiggins, E. W., and Malmberg, Q. C., "Aircraft Fuel Tank Inerting by Means of Fuel Cell Fuel Fogging," McDonnell Aircraft Company, Report No. AFAPL-TR-69-46 (May 1969)

55 Pedriani, Charles M., "Incendiary Gunfire Evaluation of a Condensate-Formed Fuel Fog Inerting System," Report No. USAAMRDL-TN-15 (May 1974)

56 Pedriani, Charles M., "Powder-Filled Structural Panels for Fuel Fire Protection", Army Research, Development & Acquisition Magazine (May-June 1981)

57 Finnerty, Anthony E., "Preliminary Evaluation of Powder Packs," Report No. BRL-MR-3641, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (December 1987)

58 Zabel, Patrick H.,"Survivability Enhancement of Advanced Survivability Test Bed Vehicle Given a Shaped Charge Hit Through the Engine Compartment Fuel Tank," Report No. ASTB-2 (31 July 1987)

59 Weatherford, W. D., Jr., et al., "Development of Army Fire-Resistant Diesel Fuel," Interim Report No. AFLRL No. 111, U.S. Army Fuels and Lubricants Research Laboratory (SwRI), San Antonio, TX (December 1979)

60 Wright, B. R. , Kanakia, M. D., et al., "Final Review of U.S. Army Fire-Resistant Fuel Program," U.S. Army Belvoir Research, Development and Engineering Center, (SwRI), Fort Belvoi. VA (December 1987)

61 Kanakia, M. D. and Wright, B. R., Investigation of Diesel Fuel Fire Vulnerability Parameters in Armored Personnel Carriers Due to Ballistic Penetration," Report No. AFLRL-194, U.S. Army Fuels and Lubricants Research Laboratory (SwRI), San Antonio, TX (March 1985)

62 Weatherford, W. D., Schaekel, F. W., et al., "Army Fire-Resistant Diesel Fuel," SAE Report No. 790926 (October 1979)

63 Wright, B. R., and Weatherford, W. D., "Investigation of Fire-Vulnerability-Reduction Effectiveness of Fire-Resistant Diesel Fuel in Armored Vehicular Fuel Tanks," Report No. AFLRL 130, U.S. Army Fuels and Lubricants Research Laboratory, SwRI (September 1980)

64 Zabel, Patrick H., "Design of Combat Vehicle Fuel Tanks to Enhance Crew and Vehicle Survivability," Tenth Symposium on Survivability/Vulnerability, San Diego, CA (10-12 May 1988)

65 Hackenbruch, Douglas J., "Cost Effectiveness of Automatic Fire Extinguishing System on the M60 Series Combat Vehicles," Report No. 79-04A, U.S. Army Tank Automotive Research and Development Command, DRDTA-V, Warren, MI (October 1979)

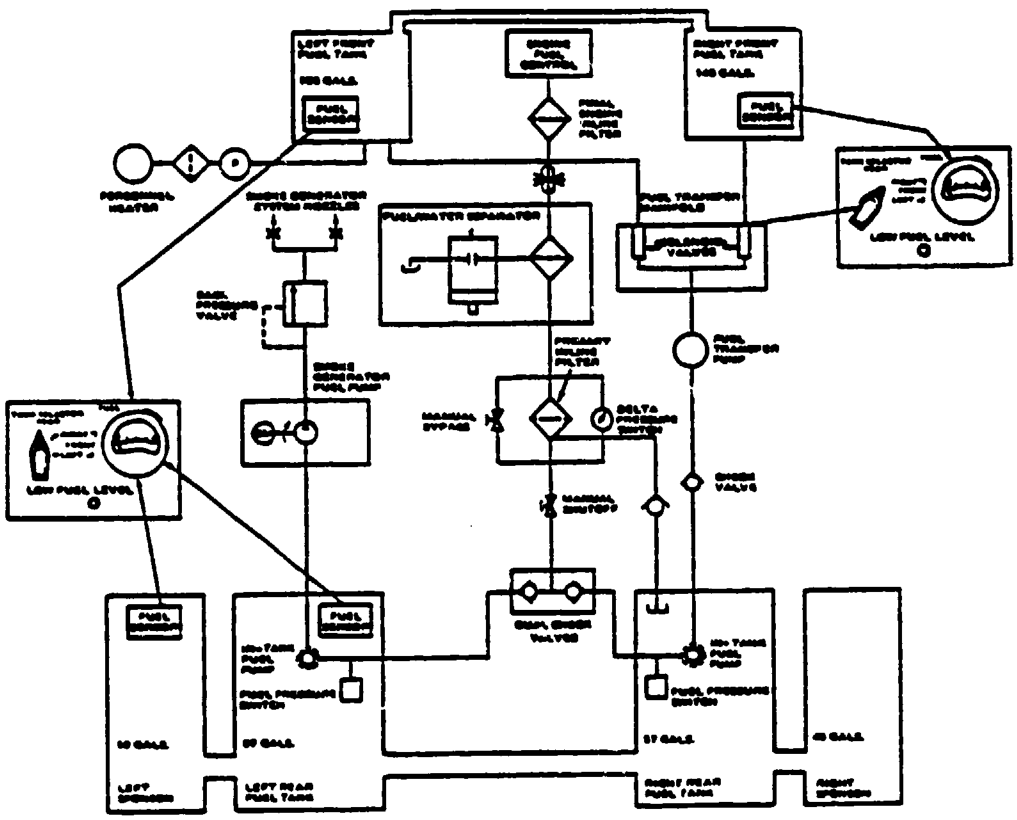
66 Zabel, Patrick H., "Shaped Charge Test Performance of Fuel Tanks for the Advanced Survivability Test Bed Vehicles," Southwest Research Institute Project No. 06-8899-003, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (27 February 1987)

67 Zabel, Patrick H., "Shaped Charge Test Performance of Fuel Tanks for the Advanced Survivability Test Bed Vehicles," Southwest Research Institute Project No. 06-8899-003, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (27 February 1987)

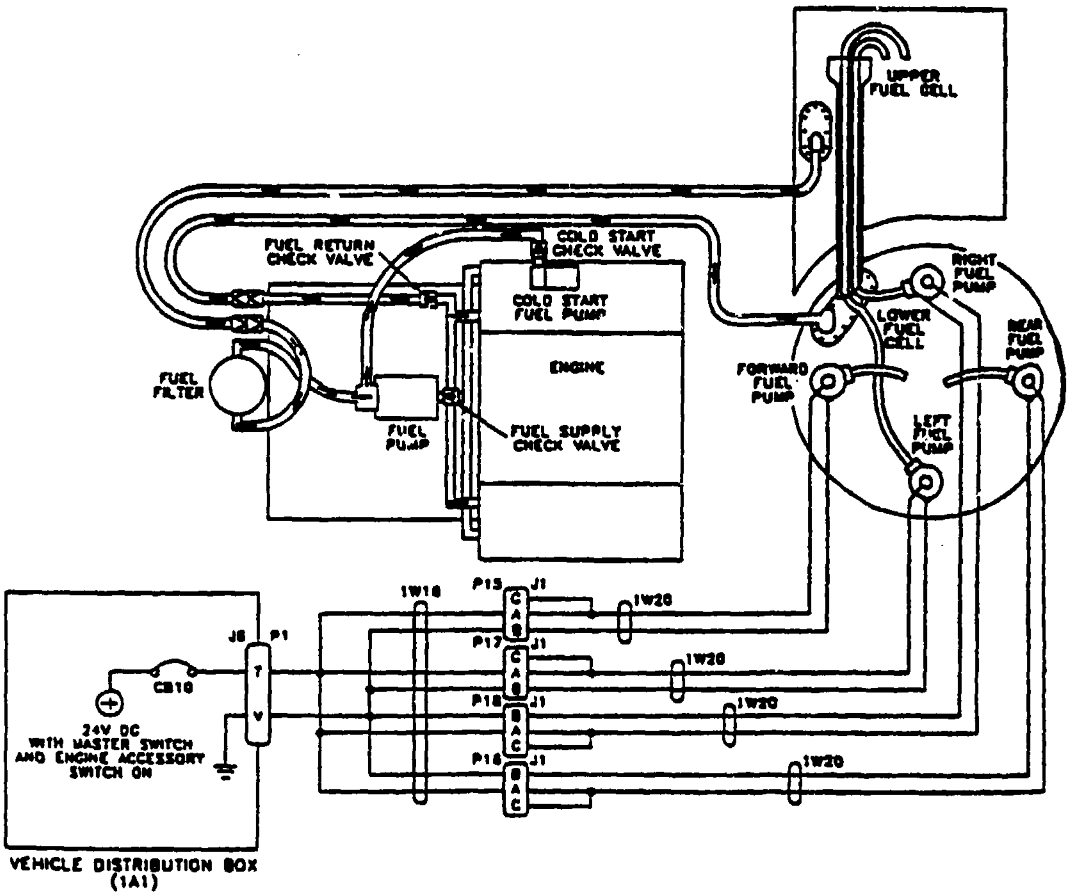
68 Finnerty, Anthony E., "Predictions of Probabilities of Sustained Fires for Combat Damaged Vehicles," Report No. BRL-TR-2875, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (November 1987)

**ADDENDUM:**

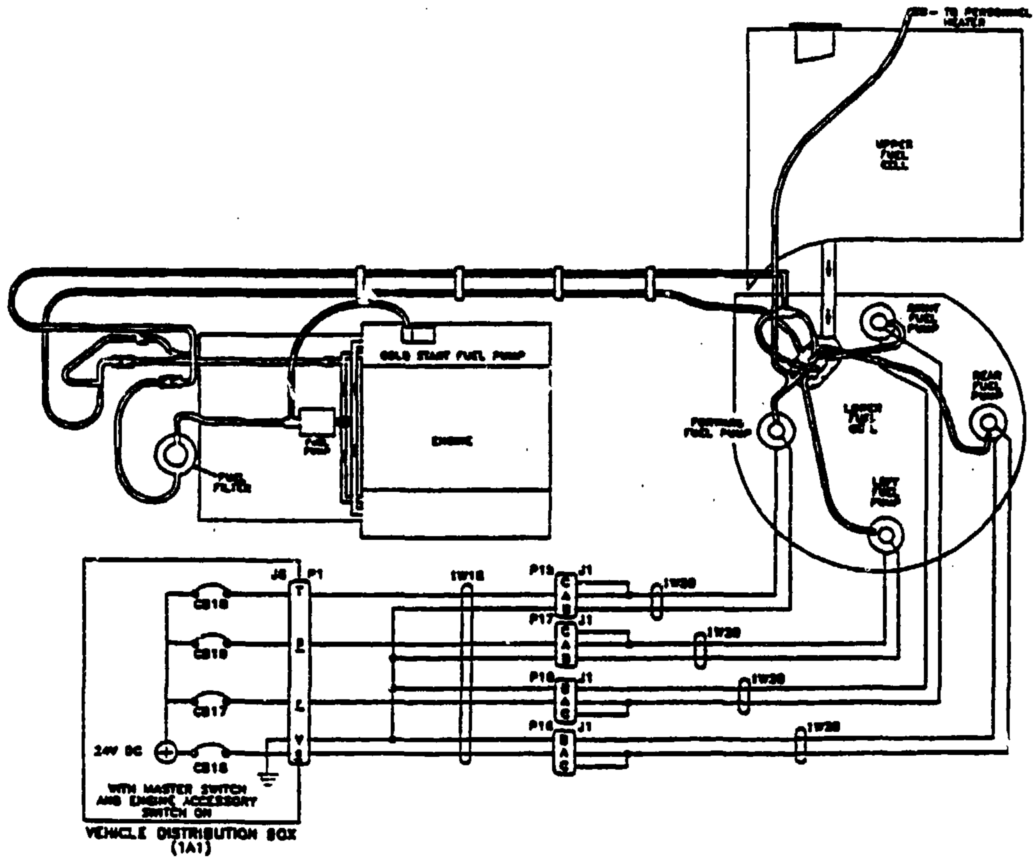
**FUEL SYSTEM SCHEMATICS**
**SELECTED VEHICLES**



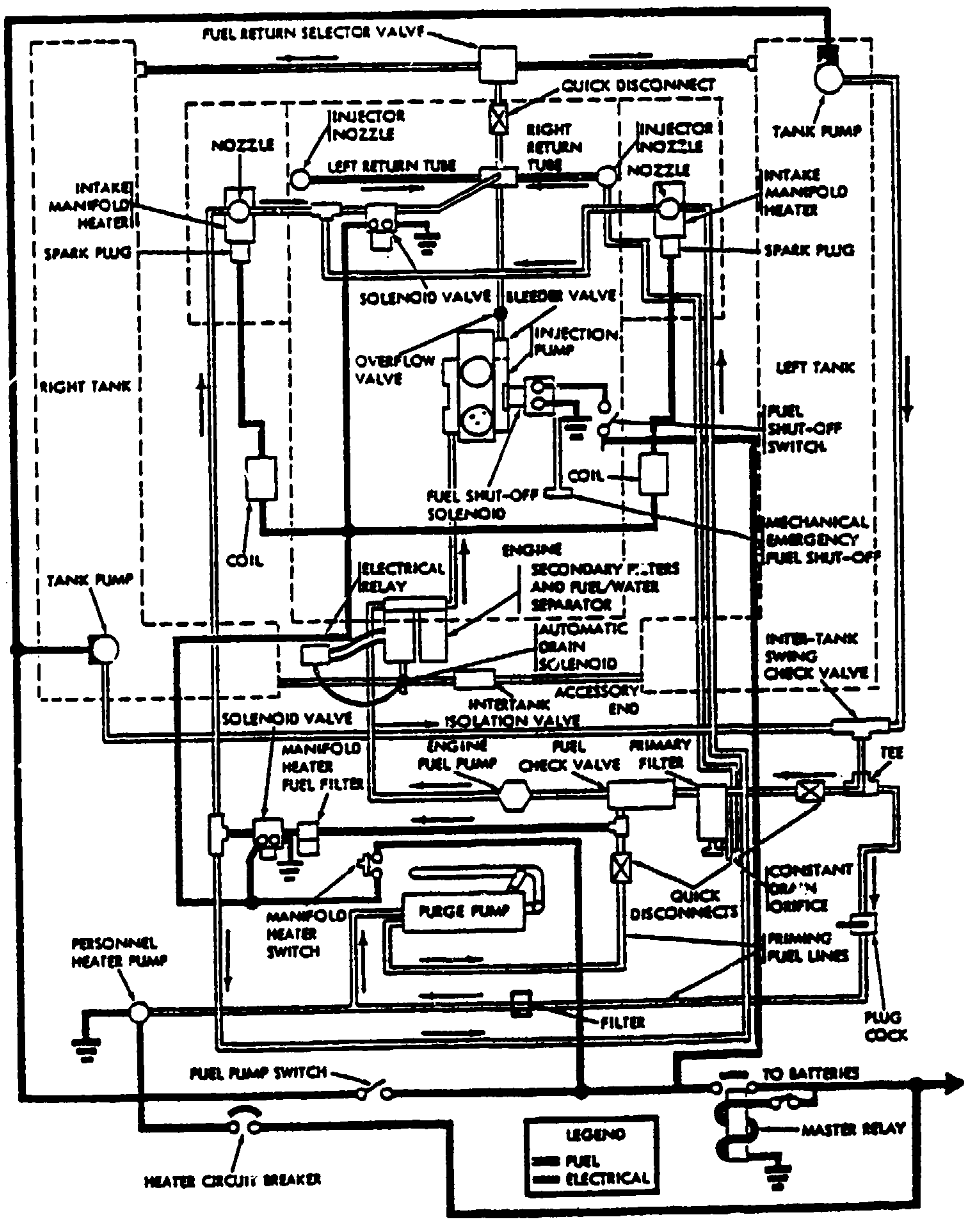
Addendum Figure 1. M1 Fuel System Schematic.



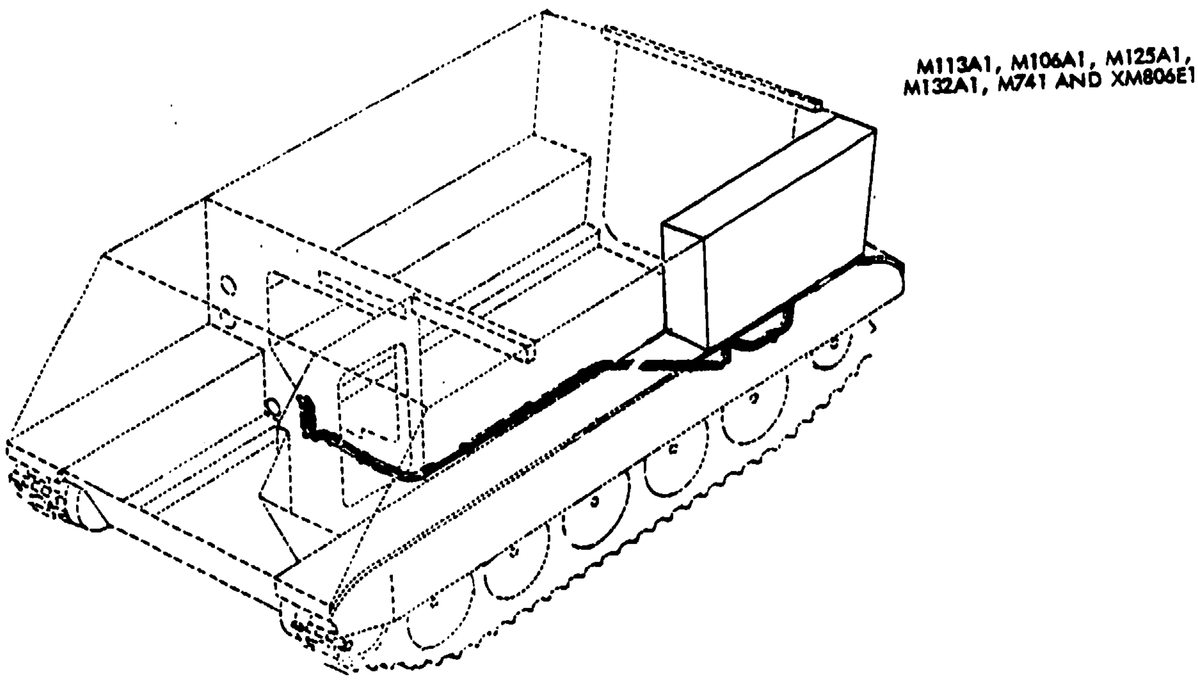

Addendum Figure 2. M2/M3 Fuel System Schematic.



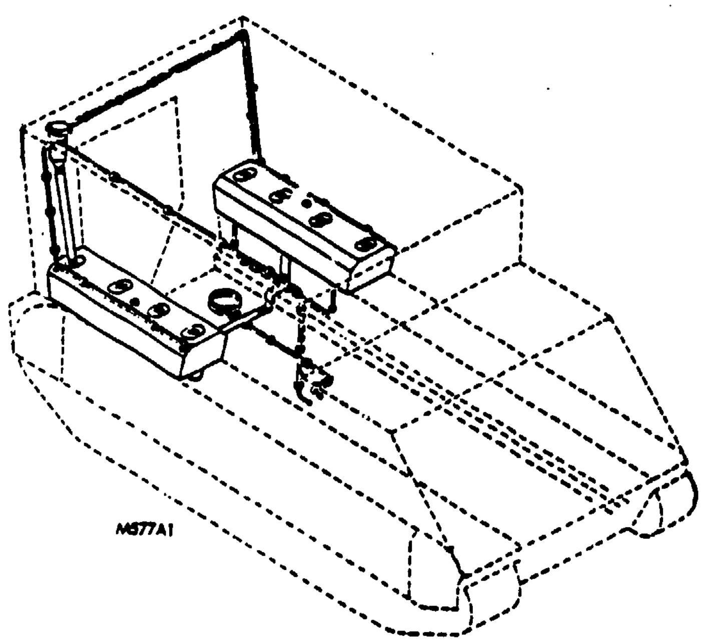

Addendum Figure 3. M2A1/M3A1 Fuel System Schematic.



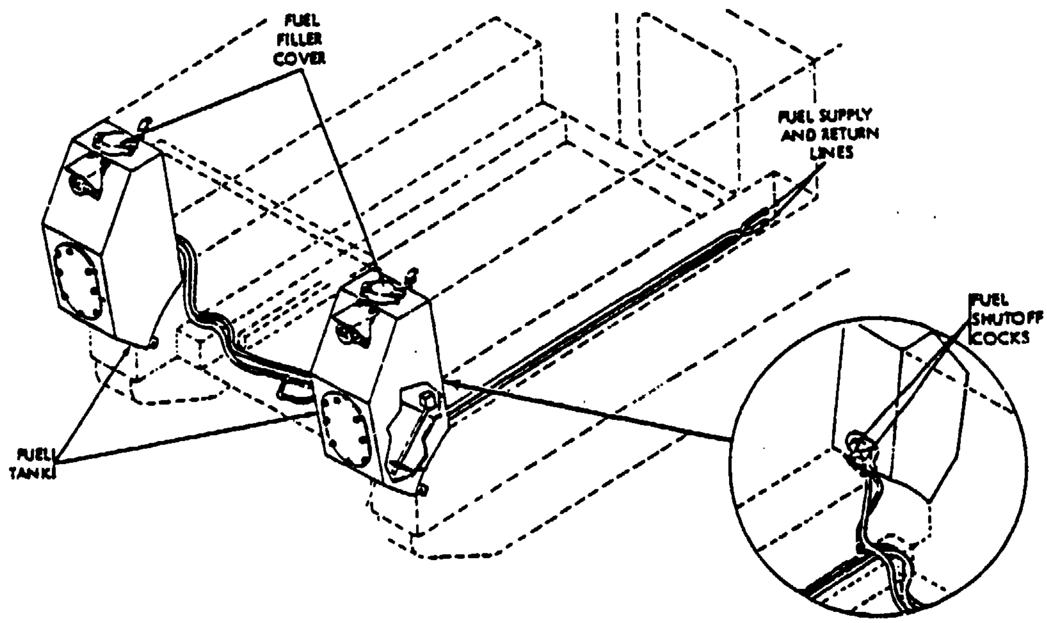

Addendum Figure 4. M60 Series Fuel System Schematic.



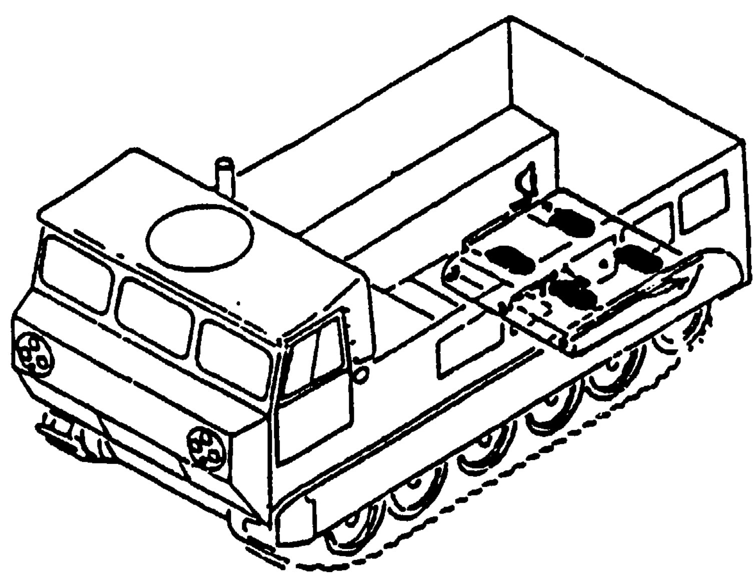

Addendum Figure 5. M113 Series Fuel System Schematics.



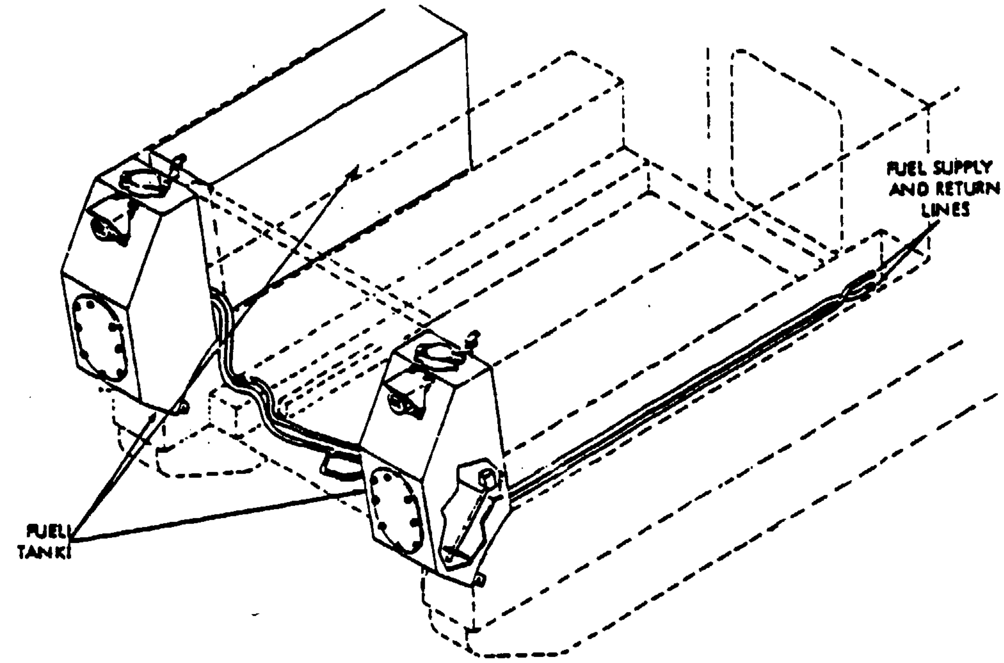

Addendum Figure 6. M113 Series Fuel System Schematic.



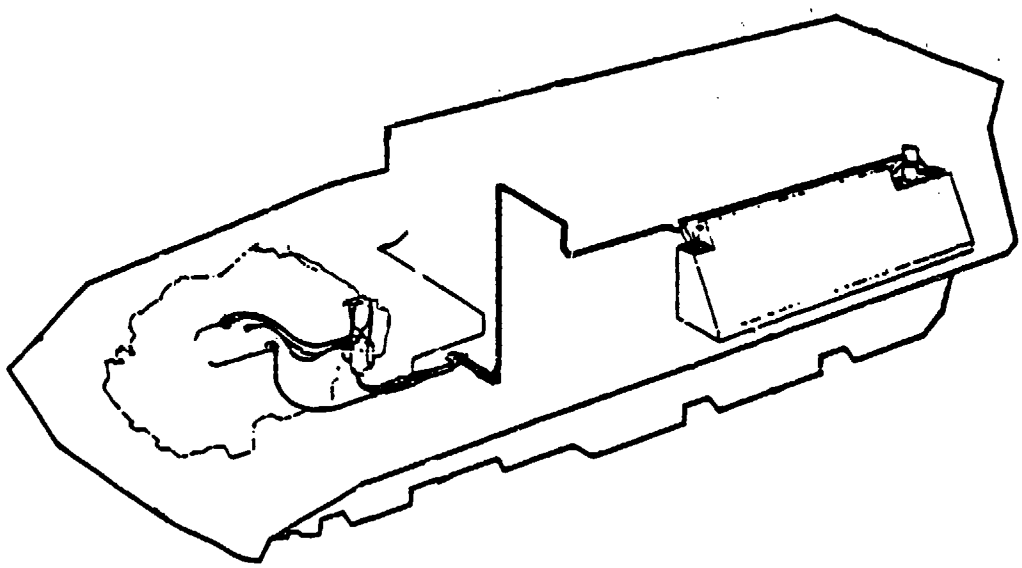

Addendum Figure 7. M113 Series Fuel System Schematics.



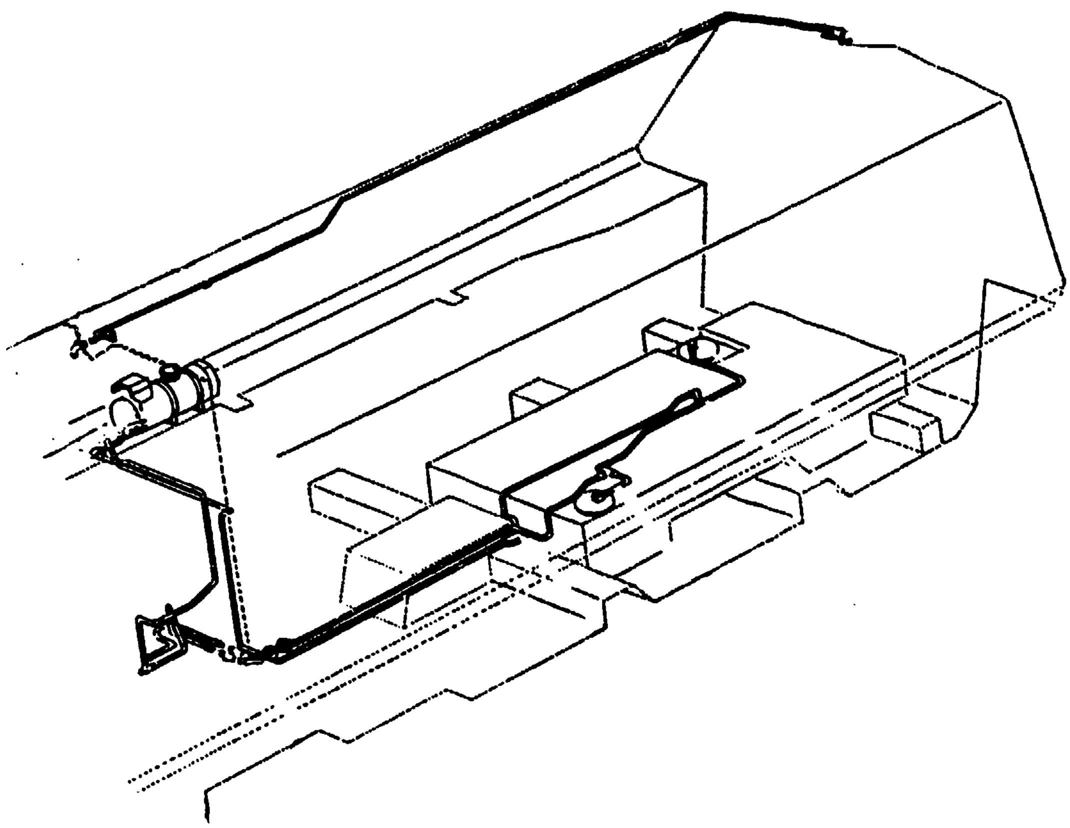
Addendum Figure 8. M113 Series Fuel System Schematic.




Addendum Figure 9. M113 Series Fuel System Schematics.



Addendum Figure 10. LAV-25, Fuel System Schematic.



Addendum Figure 11. LAV-AT, LAV-C$^2$, LAV-L and LAV-R, Fuel System Schematic.

## DISTRIBUTION LIST

| | Copies |
|---|---|
| Commander<br>Defense Technical Information Center<br>Bldg. 5, Cameron Station<br>ATTN: DDAC<br>Alexandria, VA 22304-9990 | 12 |
| Commander<br>HQ DA, ASA (RDA)<br>ATTN: SARD-TR (Mr. John Appel)<br>Washington, DC 20310-0631 | 6 |
| Manager<br>Defense Logistics Studies Information Exchange<br>ATTN: AMXMC-D<br>Fort Lee, VA 23801-6044 | 2 |
| Commander<br>U.S. Army TACOM<br>ATTN: AMSTA-DDL<br>Warren, MI 48397-5000 | 2 |
| Commander<br>U.S. Army BRDEC<br>ATTN: STRBE-VF (Mr. LaPera and Mr. Schaekel)<br>Fort Belvoir, VA 22060-5606 | 2 |
| Commander<br>U.S. Army TACOM<br>ATTN: AMSTA-CF (Mr. Orlicki)<br>Warren, MI 48397-5000 | 1 |
| Commander<br>U.S. Army HQAMC<br>ATTN: AMCDE<br>5001 Eisenhower Ave.<br>Alexandria, VA 22333-0001 | 1 |
| Commander<br>U.S. Army ASAA<br>ATTN: AMXSY-CR (Mr. Carroll)<br>Aberdeen Proving Ground, MD 21005-5071 | 1 |
| Commander<br>U.S. Army LABCOM<br>ATTN: SLCMT-TP-PM<br>2800 Powder Mill Road<br>Adelphi, MD 20783-1145 | 1 |

DISTRIBUTION LIST (continued)

| | Copies |
|---|---|
| Commander<br>U.S Army BRL<br>ATTN: SLCBR-TB-EE (Mr. Finnerty)<br>Aberdeen Proving Ground, MD 21005-5066 | 1 |
| Southwest Research Institute<br>ATTN: Patrick H. Zabel<br>6220 Culebra Road<br>P.O. Drawer 28510<br>San Antonio, TX 78284 | 1 |
| Commander<br>U.S. Army TECOM<br>ATTN: AMSTE-TA-L (Mr. Harrington)<br>Aberdeen Proving Ground, MD 21002-5066 | 1 |
| Commander<br>U.S. Army TECOM<br>ATTN: AMSTE-LI-T<br>Aberdeen Proving Ground, MD 21002-5066 | 1 |
| Commander<br>U.S. Army Safety Center<br>ATTN: CSSC-RR (COL Sisk)<br>Fort Rucker, AL 36362-5363 | 1 |
| Commander<br>U.S. Army TRADOC<br>ATTN: ATCD-MH (Mr. Parker)<br>Fort Monroe, VA 23651-5000 | 1 |
| Commander<br>U.S. Army TACOM<br>ATTN: USMC-LNO thru AMCPM-GCM<br>Warren, MI 48397-5000 | 2 |
| Commander<br>U.S. Army TACOM<br>ATTN: AMCPM-ABMS<br>Warren, MI 48397-5000 | 1 |
| Commander<br>U.S. Army TACOM<br>ATTN: AMCPM-BFVS<br>Warren, MI 48397-5000 | 1 |

DISTRIBUTION LIST (continued)

| | Copies |
|---|---|
| Commander<br>U.S. Army TACOM<br>ATTN: AMCPM-M60<br>Warren, MI 48397-5000 | 1 |
| Commander<br>U.S. Army TACOM<br>ATTN: AMCPM-M113<br>Warren, MI 48397-5000 | 1 |
| Commander<br>U.S. Army TACOM<br>ATTN: AMCPM-FAASV<br>Warren, MI 48397-5000 | 1 |
| Commander<br>U.S. Army TACOM<br>ATTN: AMSTA-U<br>Warren, MI 48397-5000 | 1 |
| Director<br>AMSAA<br>ATTN: AMXSY-MP (Mr. Cohen)<br>Aberdeen Proving Ground, MD 21005-5071 | 1 |